

ROBOTIC TOOLS FOR TRAINING AND ASSESSMENT OF ORTHOPAEDIC SURGICAL SKILLS

by

Naghmeh Zamani

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ABSTRACT

Keywords: Resident Training; Surgical Skill; Skill Assessment; Cable Robots; Haptic Robots; Impedance Admittance; Parallel Robots

Although experience within the operating room can help surgeons learn simple bone-drilling techniques, outside training may be better suited for complex procedures. This thesis investigates the use of tools from robotics to explore innovative approaches to improving the state of the art in surgical training and simulation. This entails two projects.

The first project, includes the adaptation of a rotary handpiece to evaluate bone drilling skills of orthopaedic resident physicians during the 2017 Southwest Orthopaedic Trauma Association (SWOTA) motor skills course. A total of 25 Post Graduate Year 1 (PGY1) orthopaedic residents from 6 institutions were asked to perform a bicortical drilling task 3 times before and after attending a motor skills course. Kinetic and kinematic data were collected using force, acceleration, and visual sensors. A total of 16 parameters were measured - those different after the course to a statistically significant degree were: over-penetration, skiving, preparation time, drilling time, palmar-dorsal vibration, maximum drilling force, and maximum RPM. The interdependence of these parameters - taken separately for pre- and post-course performance are presented. Noteworthy correlations include: over-penetration with force (0.65), palmar-dorsal (P-D) toggle (0.65), vibration in P-D (0.53), time (-0.41), and RPM (-0.36); time with both RPM (0.38) and P-D toggle (-0.40); and force with both RPM (-0.41) and P-D toggle (0.32). The correlation data presented provides insight into patterns between measured parameters as to where performance metrics are and are not coupled. Evidence for motor skill acquisition across both short and long-time scales is elucidated.

In the second project, a Plates and Cables (PAC) haptic device is built, which presents first steps in the ambitious design of a hybrid impedance- admittance haptic device that targets simulation of bone drilling and related tasks. The version presented here is optimized for the high axial forces needed for simulating the use of a surgical drill or bone awl. At this stage we are presenting a simplified prototype of the mixed impedance and admittance haptic device optimized for applications, like bone drilling, spinal awl probe use, and other surgical techniques where high force is required in the tool-axial direction and low impedance is needed in all other directions. The performance levels required cannot be satisfied by existing, off-the-shelf haptic devices. This design may allow critical improvements in simulator fidelity for surgery training.

The device consists primarily of two low-mass (carbon fiber) plates with a rod passing through them. Collectively, the device provides six DOF. The

rod slides through a bushing in the top plate and it is connected to the bottom plate with a universal joint, constrained to move in only two-DOF, allowing axial torque display the user's hand. The two parallel plates are actuated and located by means of four cables pulled by motors.

The forward kinematic equations are derived to ensure that the plates orientation remains constant. The corresponding equations are solved using the Newton-Raphson method. Then, we present the predicted distribution of location error, cable velocity, cable tension and force for the device. These results and preliminary hardware fabrication indicate that this design may provide a revolutionary approach for haptic display of many surgical procedures by means of an architecture that allows arbitrary workspace scaling. Scaling of the height and width can be scaled arbitrarily.

Finally, the inverse, forward and other functions are implemented to the robot controller. Torque to position controller is used by using PID with feed-forward for compensate the nonlinearity of dynamic coupling in the system. In this controller, switch between position and current modes would be fast and easy.

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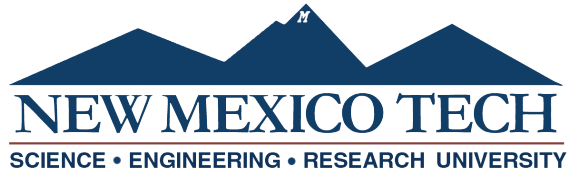
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This thesis is accepted on behalf of the faculty
of the Institute by the following committee:

David Grow

Academic Advisor

David Grow

Research Advisor

Kooktae Lee

Committee Member

Christina Salas

Committee Member

I release this document to the New Mexico Institute of Mining and Technology.

Naghmeh Zamani

Date: 5/ 23/ 2018

CHAPTER 1

INTRODUCTION

1.1 Background

Safety in surgeries is now given so much priority that surgeons are required to comply with standards—a circumstance surprisingly different from the past. For instance, in 1922, Dr. Halsted at Johns Hopkins Hospital pioneered the philosophy of safe surgery by establishing basic surgical procedures such as the use of rubber gloves in the operating room (Fig. 1.1 shows a surgery circa 1992). During the latter part of 19th century and early part of 20th century, there were very few surgeons. Those few surgeons were reluctant to instruct others, resulting in most surgeons being self-taught. Dr. Halsted developed a training program for the surgeons for the first time, which progressed to today's surgical residency training programs [3, 4].



Figure 1.1: Surgery circa 1992 [1].

Orthopaedic surgery demands a range of motor skills that require deliberate training. Historically, these skills were primarily acquired in the operating room (OR). While this may be an effective method of training for simple fractures

or low-risk cases, for more complicated operations or high-risk situations (spinal surgery, potential for vascular or nerve injury, etc.), the motor skills tasks should be simulated in the lab prior to performing the tasks in the OR. Orthopaedic surgery was one of the earliest surgical fields to teach surgical skills to residents outside of the OR. In 1975 Lippert et al. offered a motor skills course at the University of Washington [5]. In the time since, the modes for and interest in this type of training have continued to grow [6, 7]. Meanwhile, an increasingly clear picture has been developed for patient safety [8] and costs associated with surgical complications [9]. While additional in-OR training remains critical, it is expensive. It has been estimated that the additional time associated with the inclusion of residents in general surgery cases results in a national annual cost of 53 million dollars [10]. Simulated surgery has several clear advantages, including reduced stress to the resident. Another advantage of simulation (or focused skills lab) is the ability to train a particular aspect, which has been shown to result in more rapid acquisition of particular skills [6, 11, 12, 13, 14, 15, 16, 17]. As of July 2013, prompted by the quality initiative set forth by the Patient Protection and Affordable Care Act, the American Board of Orthopaedic Surgeons (ABOS) and the Residency Review Committee (RRC) for Orthopaedic Surgery have mandated formal motor skills training outside of the OR [18, 19].

1.2 Improving Orthopaedic Surgical Results

In orthopaedic surgery, it is essential to improve both the operation room's tools and training-methods. A large number of orthopaedic procedures involve drilling holes in bone. It is a required skill, not only for orthopaedic surgery, but also in many other fields like neuro-, plastic and reconstructive, craniomaxillo-facial and ear, nose and throat surgery [20]. There are numerous variables that can affect the performance of orthopaedic residents. Lots of previous research tried to predict residents' success on the American Board of Orthopaedic Surgery (ABOS) examination. For instance James H. Herndon et al. tried different variables that might suggest or predict residents performance on the ABOS. They had done this study on 161 residents and they found objective resident's performance predictors on this examinations [21].

1.2.1 Improving the Tools

The drilling of a "good" hole entails precise location and orientation, and avoids the use of excessive force, over-penetration, drilling time, toggle, high temperature, or skiving [13, 14, 15, 16, 17, 18] (Fig. 1.2 shows the importance of location and orientation of a drilled hole in a fractured leg, which should be in perpendicular to the fracture line). Friction during bone drilling can generate a high temperature because of energy conversion from mechanical work to

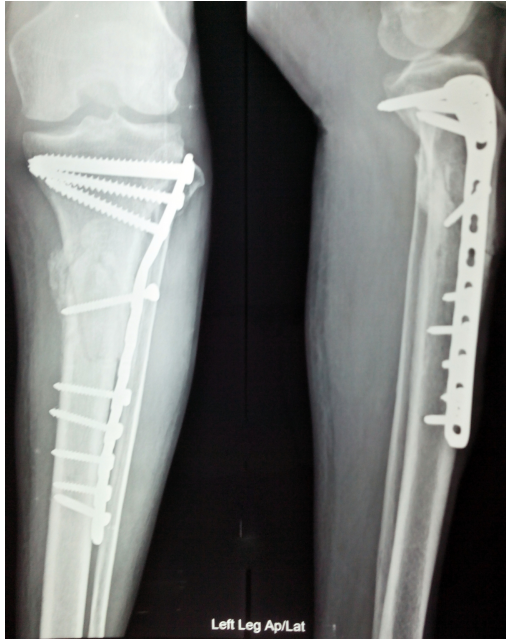


Figure 1.2: Anterior and lateral view x-rays of fractured left leg with internal fixation [2].

thermal. An excessive temperature can cause the necrosis (death) of bone, a phenomenon termed osteonecrosis, or the impairment of osteogenic potential. For reducing the temperature during drilling some methods like irrigating with sterile saline are used [20]. The obvious parameters related to the temperature are drill bit speed and applied force. Because of the importance of drilling force and speed, many previous studies have measured these parameters in different ways. Hessinger et al. designed a handheld drill to measure the axial thrust force during drilling [22]. Also, in [23], the authors compared the measured force and torque of drill bit on both artificial and human bone. In [24], threshold force is detected during real-time drilling by using Proportional-Derivative (PD) motion and force control. One result of previous work found that an increase in the speed and force resulted in decreased drilling time, which caused a decrease in consumed energy [25]. This result suggests that higher force can be useful in reducing the temperature. Drill angle is another important issue during drilling. In [26], many different related angles between the bone and drill bit, which cause drilling improvement were investigated. Skiving is the other important factor during drilling because it can damage tissues as well as change the target hole position.

1.3 Development of Robotic Tools for Orthopaedic Surgical Skill Training

In recent decades, innovation approaches have been explained. Examples of this include developing robotic arms to assist in performing the drilling

task with minimum error [27] or designing a new robot like DRIBON as a bone drilling guide [28]. Despite the precision of these robots, they are only just now being used, in part due to safety concerns [27].

1.3.1 Using Haptics for Surgical Simulation

The goal of haptic technology is to allow technology to interact with human touch. This technology, combined with virtual reality can provide a superior surgical simulator. Incorporating haptic technology into the training system can provide realistic force and torque feedback to the hand and can simulate the real world for the user, which are the most important requirement for surgical robots. There are two main major types of haptic robots: impedance and admittance. Impedance robots have very low inertia and friction and they are back-drivable. Admittance robots tend to have very high friction and inertia, it can provide more force and they are not back-drivable [29].

Some of the new surgical robots are using haptics and teleoperation for operating room assist. In [30], the authors design a telerobotic-assisted drilling system, which scales the position and force to get more precise drilling and it can detect the hazard by force sensation. In [31, 32], a bone drilling simulation haptic device, with six degrees of freedom was developed. In this research they have rendered thrust force and torques by a haptic device.

1.3.2 Haptic Cable Robots

One class of the parallel manipulators is the cable-direct-driven- robot (CDDR), which works with flexible cables instead of rigid links, where each cable is connected to one tensioning motor. When designing a haptic system, it is desirable to maximize the workspace, both translational and rotational. This design goal must be balanced against engineering design cost such as cable load, platform weight, the dimensions of the surrounding environment, and the size of the mobile platform itself. This requires a description of the workspace that provides quantitative and comparable values among a set of configurations. Cable robots have very low weight and low inertia. They can be made for any desired speed and workspace, ranging from very small finger design to large-scale robots for inspection of airplanes [33]. These mentioned features are very useful for haptic robots. A lot of previous work used the CDDR and cable haptic robots for both impedance and admittance mode [34, 35, 36]. One of the earliest CDDRs was in early 1980s, a robot made by NIST, which included six cables instead of hydraulic cylinder legs for holding a load platform. The most important point in the cable robots is making sure that cables are in tension, and in this design gravity helps them to ensure this aspect. This design was a modified Stewart platform. The Defense Advanced Research Projects Agency (DARPA) tried to determine the performance of this robot. Their main goals were stiffness optimization and active

oscillation damping. They wanted to modify and control the system to get use in the industrial robots, which requires them to move everywhere on the factory floor [37].

1.4 Specific Aims

This thesis investigates the use of tools from robotics to explore innovative approaches to improving the state of the art in surgical training and simulation. This entails two **Specific Aims**:

Specific Aim 1 Capture the relevant performance parameters during a simulated bone drilling procedure in 2017 Surgical Skills Training Course held by the Southwest Orthopaedic Trauma Association (SWOTA) for Year 1 orthopaedic residents. This is covered in Chapter 2.

Specific Aim 2 Design a platform for simulating bone drilling and other procedures that require large force in one, tool-oriented direction, and low force with high speed in the orthogonal directions. This is covered in Chapter 3.

CHAPTER 2

ROBOTIC EVALUATION OF ORTHOPAEDIC SURGEONS DURING BONE DRILLING

2.1 Introduction

Although experience within the operating room can help surgeons learn simple bone-drilling techniques, outside training may be better suited for complex procedures. We adapted a rotary handpiece to evaluate bone drilling skills of orthopaedic resident physicians during the 2017 Southwest Orthopaedic Trauma Association (SWOTA) motor skills course. A total of 25 PGY1 orthopaedic residents from six institutions were asked to perform a bicortical drilling task three times before and after attending a motor skills course. Kinetic and kinematic data were collected using force, acceleration, and visual sensors (Fig. 2.1).

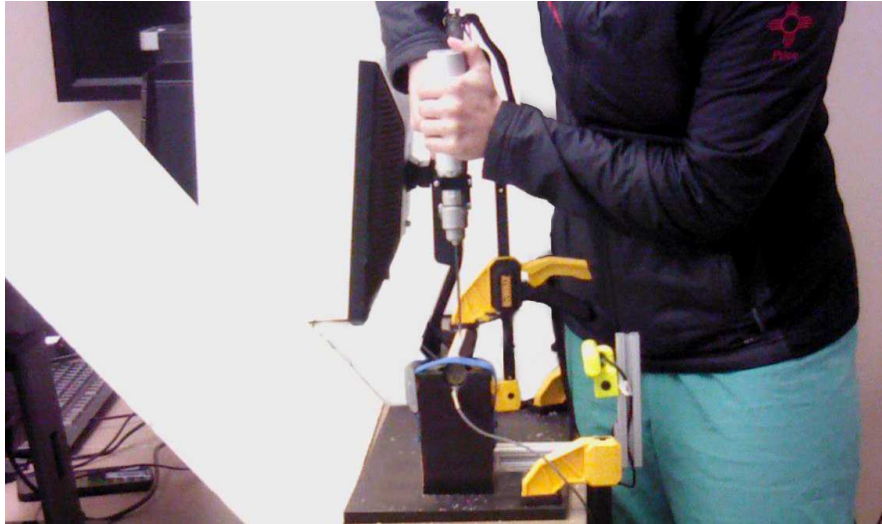


Figure 2.1: A variety of parameters critical to orthopaedic drilling are measured using the device shown. The major components are a modified Stryker System 5 rotary handpiece with dual trigger and drilling attachments, a synthetic bone fixture with integrated force sensor and camera, and a variety of electronic and computer components to read from sensors, analyze data, and allow visualization of the results.

2.2 Methods

2.2.1 Hardware

Fundamentally, the hardware design aims to facilitate quantification of all parameters related to the failure or success of drilling a “good” hole in the context of orthopaedic surgery. The device used here is an improvement upon similar devices used in previous years [38, 39, 40, 41]. With each iteration, the goal has been to maximally preserve (or improve upon) the utility compared to previous devices while reducing device cost, size, and complexity. Fundamentally, the hardware consists of: 1) a modified Stryker System 5 rotary handpiece with dual trigger and drilling attachments (Kalamazoo, MI); 2) a synthetic bone fixture with integrated force sensor and camera; and 3) a variety of electronic and computer components to read from sensors, analyze data, and allow visualization of the results. Additionally, a thermal imaging camera was used to observe specimen heating during drilling (FLIR T640, Nashua, NH).

Parameters measured include: drill orientation and vibration, over penetration, applied force, drill RPM (revolution per minute), skiving, and drill bit temperature. Drill kinematics, specifically drill orientation (roll, pitch, yaw), vibration, and rotational speed are measured using a combination of a nine-DOF orientation sensor (Bosch BNO055, Stuttgart, DE) and an external, calibrated camera. The accelerometer as well as other hardware allowing for constant external power supply were assembled into the battery housing, as shown in Figure 2.2. External power was used to ensure that drill performance does not change with variations in battery performance over time and from subject to subject.

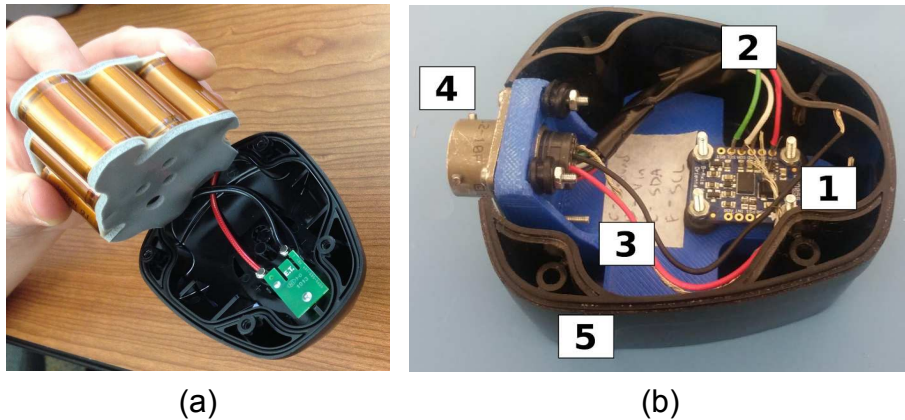


Figure 2.2: The battery bay (a) for the orthopedic drill was modified to house electrical hardware components. Notable components are: (b1) an absolute orientation sensor for measuring drill orientation, (b2) wiring harness, (b3,4) wiring and bayonet connector to permit use of external power supply, and (b5) the battery housing, whose form was changed minimally to permit these modifications.

The synthetic bone fixture included a camera mount ensuring eliminating the need for re-registration and incorporated a load cell to measure the force applied during drilling (Fig. 2.3-(a)).

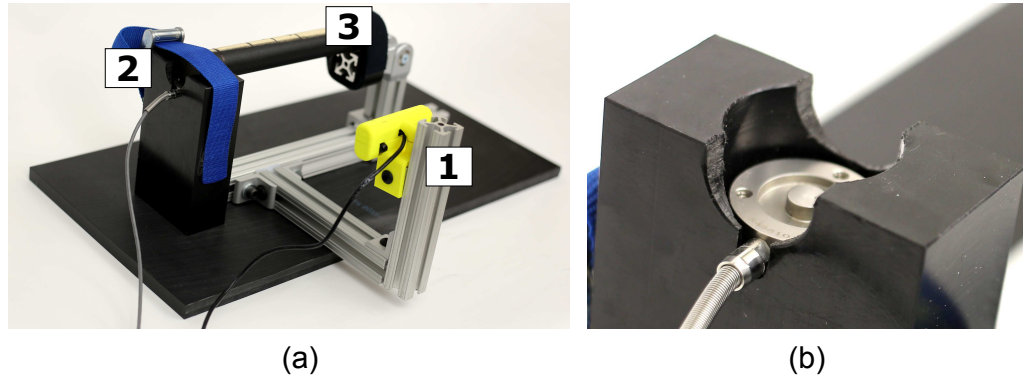


Figure 2.3: A custom fixture was built to hold the bone analog, support a small camera (1) used, in part, for measuring over-penetration, and a load cell (2) for measuring applied load. At one end of the fixture, the sample is supported by a hinge joint (3) and the button load cell (2) provides the support force at the other end. Actual force measurement required knowing where along the length of the bone the drill was positioned. This was controlled for during the experiment.

Drill speed was measured using a small magnet attached to the chuck along with a reed switch and associated electronics attached to the drill body (Fig. 2.4).



Figure 2.4: Drill speed was measured using a small magnet attached to the drill chuck. Adjacent to this, and supported by the drill body, a reed switch allowed measurement of chuck rotation. This signal was decoded by a computer algorithm.

Data from the kinematic sensors and camera were recorded using an Arduino Uno microcontroller and a desktop computer (Intel Core i7, 6700 3.4 GHz processor, 8 GB RAM). Force data were recorded using a National Instruments data acquisition system (cDAQ) and a second desktop computer (dual core Intel, 2.4 GHz Processor, 32GB RAM). Sufficient performance required tuning and careful synchronization of these data streams. Among the technical solutions, a Python script was used to synchronously pull sensor data from the Arduino serial ports (one thread) while pulling frames (separate thread) from the camera at 52 frames per second. A manual control box was used to cue data recording on both machines. Figure 2.5 shows some representative parameters obtained.

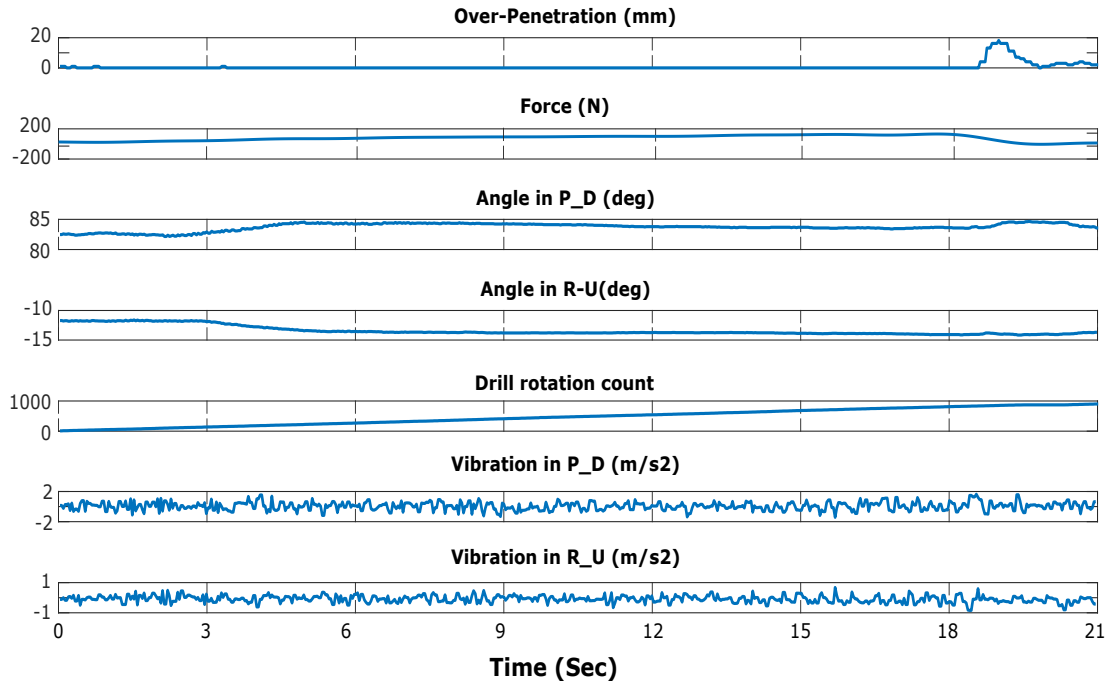


Figure 2.5: Representative data for some of the parameters measured. Over-penetration was measured using a camera (52 frames per second) along with accelerometer data (45 Hz). Here over-penetration is calculated to be zero until at approximately 19 seconds, when it begins to spike to 20 mm. Force data were recorded using a load cell and NI cDAQ at 1.4 kHz. Here, the force is seen to steadily increase to 110.9 N, then begin to drop shortly before the drill exits the sample. Similarly, five other parameters that describe drill orientation (both in the palmar-dorsal and radial-ulnar directions), drill RPM (rotation count), and drill vibration are depicted (all captured at 45 Hz).

2.2.2 Human Subjects

This study was approved by the Institutional Review Board at University of New Mexico (HRRC#15-087). Subjects were recruited during the 2017 Surgical Skills Training Course held by the Southwest Orthopaedic Trauma Association (SWOTA) for Year 1 orthopaedic residents in Albuquerque, NM. This is an American Board of Orthopaedic Surgery (ABOS) residency surgical skills training course with participation from orthopaedic surgery residents from New Mexico, Arizona, Texas, and Nevada. In all, 25 residents were included (9 female, 16 male).

2.2.3 Task Design

Prior to the start of the course, participants completed a survey that was used to quantify their prior experience and other relevant factors (complete survey included in Appendix A) During the task, each participant was asked to drill a perpendicular hole through the entire cross section of a one-inch aspen dowel, while taking into consideration any performance factors relevant to bicortical drilling in a clinical setting. This task was performed three times (a fourth hole was requested if a false start, measurement error, or the like effected data collection for any of the three). Participants in the course were then subject to guided training for three days of training including: splinting and casting, external fixation, K-Wire use, internal fixation basics, olecranon osteotomy, plating basics, distal femur locking plates, proximal tibia locking plates, incision, exposure, and soft tissue handling (cadaver), compartment syndrome, distal radius repair, and fingertip repair. Following the third day of the training period, we asked each participant to repeat the task.

2.2.4 Data Capture and Analysis

Over-penetration was measured in real time by combining the orientation of the drill per the accelerometer with a camera (Creative HD 720 p, Singapore) view of the underside of the drilling sample. During drilling, generated debris tends to fall in the area viewed for over-penetration by the camera. In order to ignore this noise source, eroding, dilating, and Gaussian filters were used to differentiate the drill bit from the debris (Fig. 2.6). Additionally, care was taken to color the drilling sample, background, and in the selection of the drill bit to maximize the visual contrast (Fig. 2.7). After all of the individual parameters were processed, the Matlab function *corrplot* was used to determine correlation coefficients (parameter interdependence). Pre- versus post-course performance differences were tested for statistical significance using Matlab's *anova1* function (single factor).

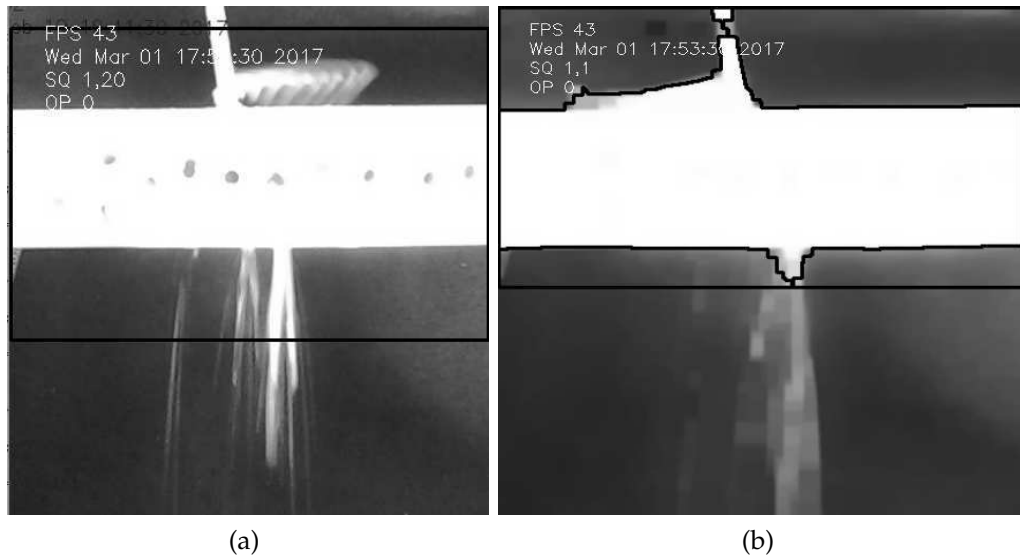


Figure 2.6: As shown in (a) the dust made lots of noise in frames, which was preventing from finding the exact position of the drill bit in every moment. (b) shows the a noisy frame after filter process.



Figure 2.7: Shows the ideal case for measuring over penetration because the dust is the same color as the background. Drill bit and the prosthetic bone surface has enough contrast with the rest of background without presence of any light.

2.3 Results

Information gathered through the survey, experimenter observations, and by means of the integrated data acquisition system is summarized in Table 1. Analysis of the data was made separately for pre- and post-course performance. The changes that were statistically significant included: increase in vibration in the palmar-dorsal (P-D) direction, increase in drill RPM, increase in drill force, drilling time ($p < 0.01$, pre mean = 8.28, post mean = 9.34), reduced frequency of skiving ($p < 0.01$, pre mean = 22, post mean = 6), and preparation time ($p = 0.01$, pre mean = 27.3, post mean = 9.7). In Figures 2.8–2.12 the box plot of these parameters based on the participants residency program is shown.

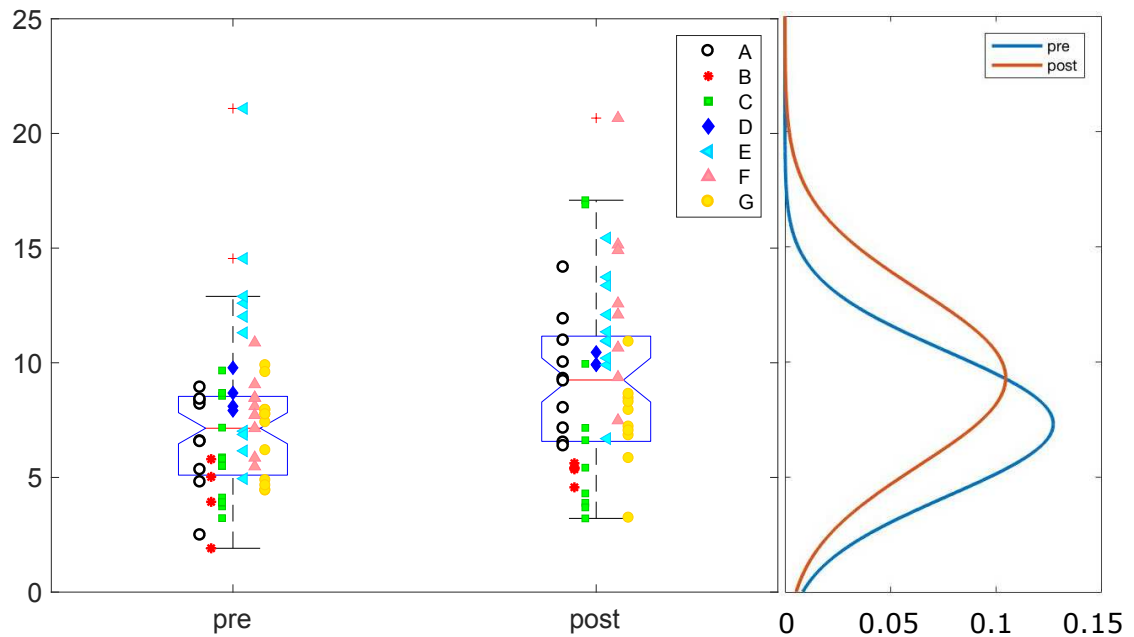


Figure 2.8: The pre- versus post-course performance is different in drilling duration ($p = 0.0022$). The "+" symbol shows the automatically detected outliers. A–G are the residency programs.

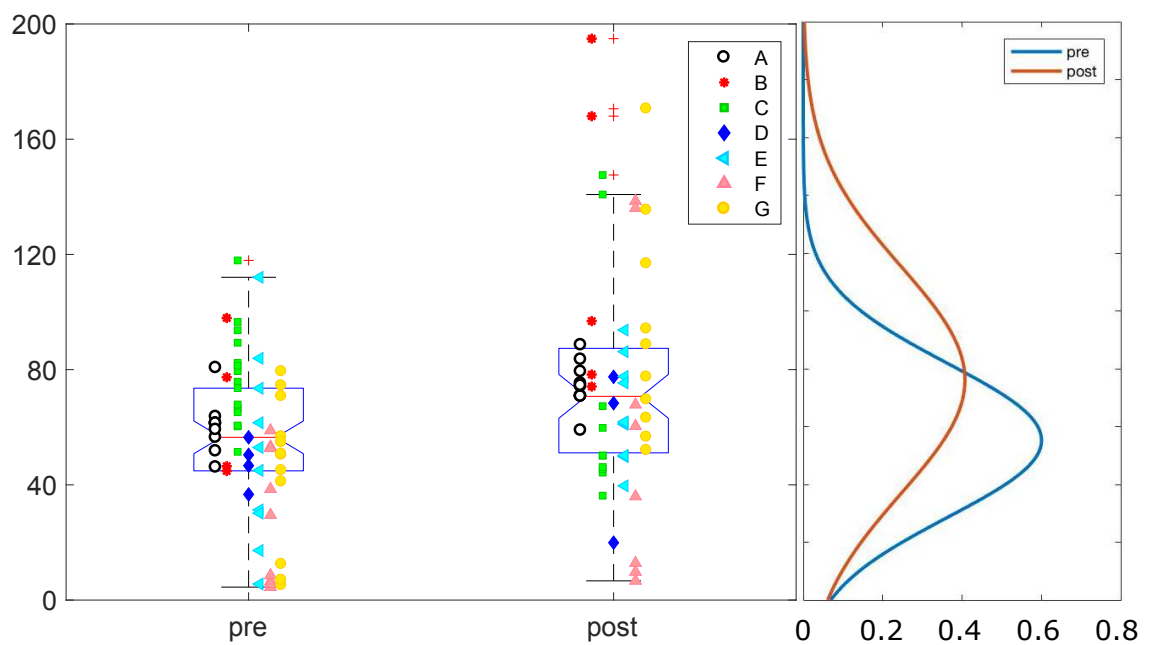


Figure 2.9: The pre- versus post-course performance is different in drill force ($p=0.0038$). "+" symbol shows the automatically detected outliers. A–G are the residency programs.

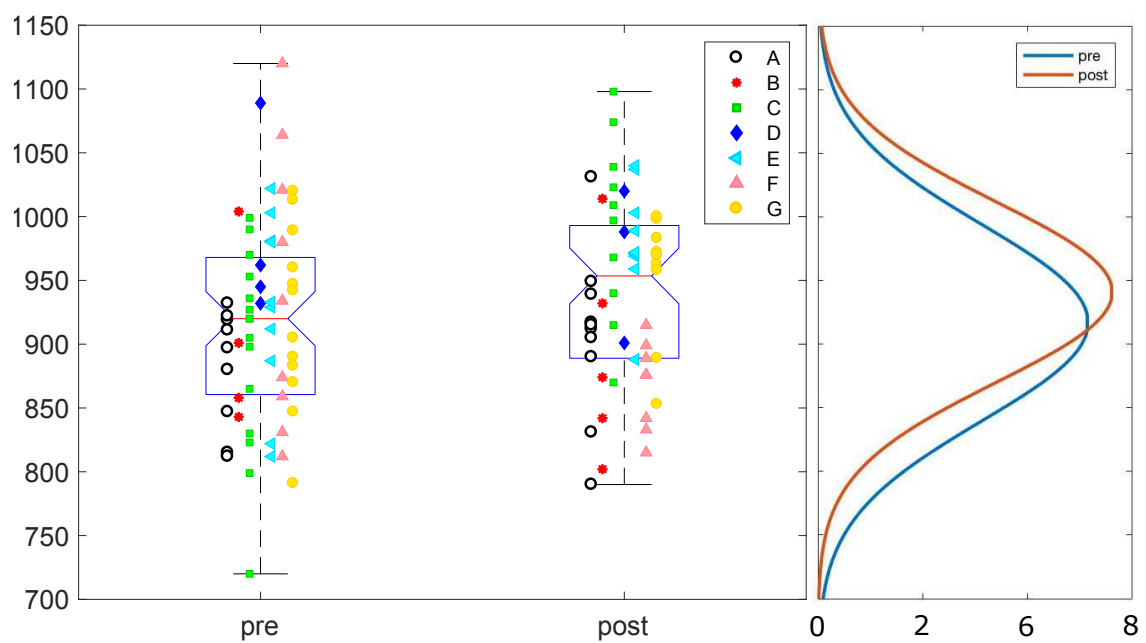


Figure 2.10: The pre- versus post-course performance is different in drill RPM ($p=0.0736$). A–G are the residency programs.

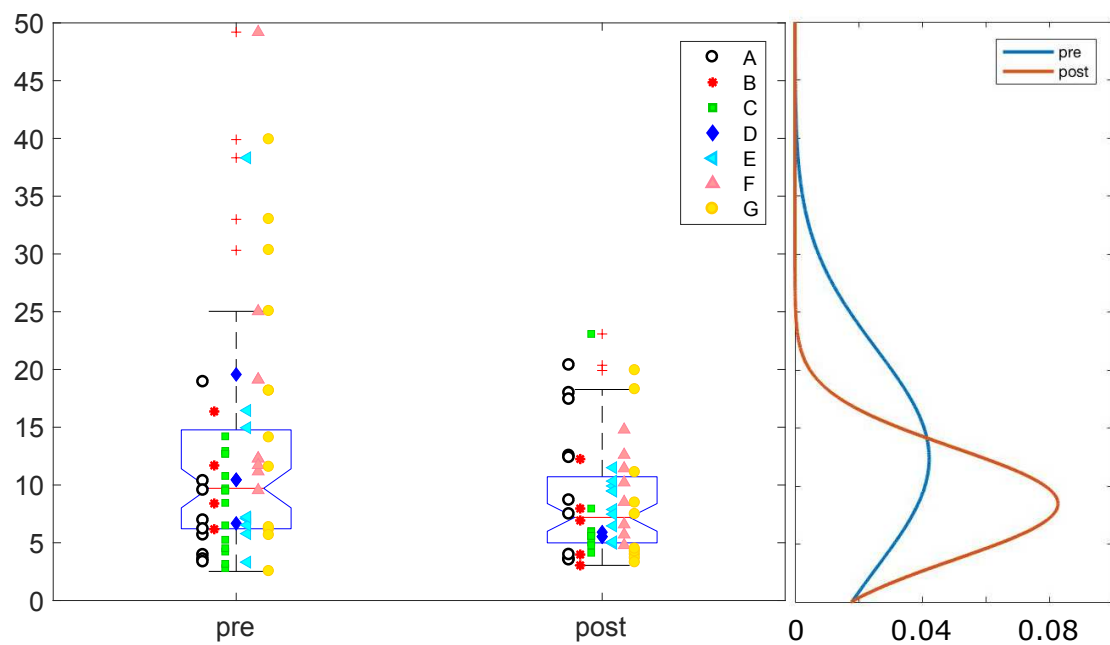


Figure 2.11: The pre- versus post-course performance is different in preparation time ($p=0.0118$). The "+" symbol shows the automatically detected outliers. A–G are the residency programs.

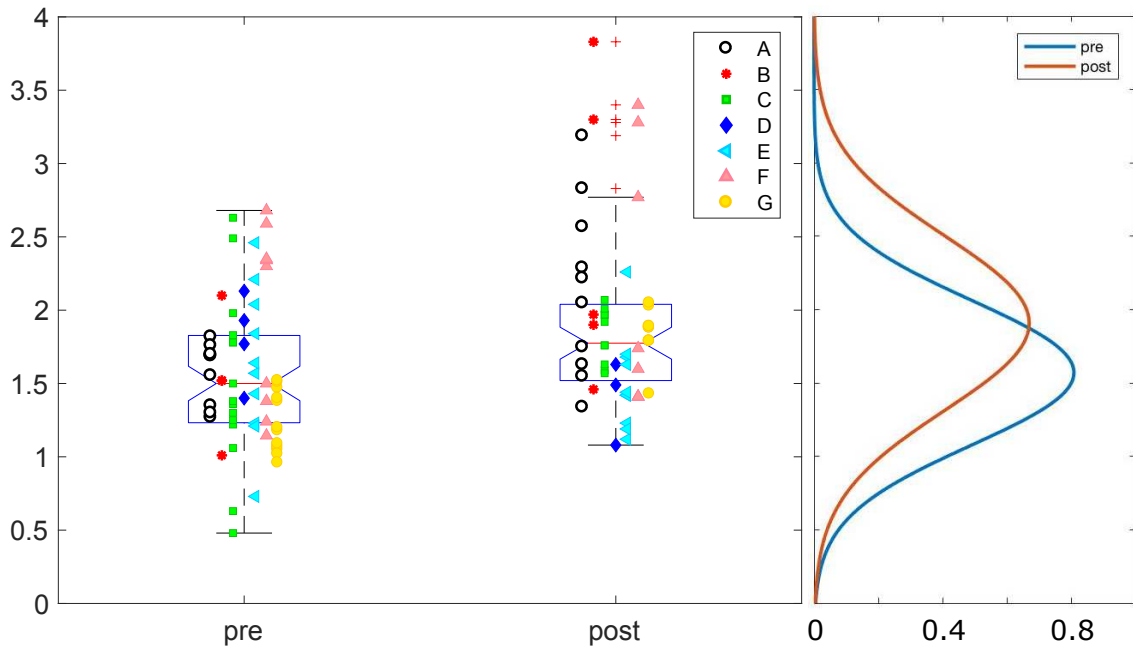


Figure 2.12: The pre- versus post-course performance is different in vibration in the Palmar-Dorsal direction ($p=0.001$). The "+" symbol shows the automatically detected outliers. A–G are the residency programs.

Other changes that are noteworthy but not statistically significant (see Table 2.1 for p -values) include: reduction in over-penetration (28.8 mm to 18.2 mm); reduction in skiving (22% to 6%); and reduction in preparation time (and total time consequently; 27.3 seconds to 9.65 seconds). The approach taken by each resident was observed to vary more than expected. Quite a few trials (11 of 75 pre-test, 13 of 69 post-test) were not correctly recorded or had to be eliminated during the trial analysis that followed because of some unanticipated movement pattern that resulted in a miscalculation of one or more of the sixteen measured parameters. Beyond the variables themselves, much can be inferred from their correlations (Figures 2.13 and 2.14). First, the strength of correlations between parameters for the post-course test is generally stronger. Focusing there, among those, noteworthy correlations include: over-penetration with drilling force (0.65), P-D toggle (0.65), P-D vibration (0.53), drilling time (-0.41), and drill RPM (-0.36); drilling time with both drill RPM (0.38) and P-D toggle (-0.40); and drilling force with both drill RPM (-0.41) and P-D toggle (0.32). Effect of Experience Level on performance was not strongly presented in the data. It should be recalled, though, that this was assessed simply as a self-reported parameter obtained through the survey ("estimate number of surgeries performed and viewed"); responses range from 40 to 200. Interestingly, none of the residents indicated separately

how many they had only viewed versus those they performed, suggesting that they consider those two experiences as equivalent, though it seems clear they would not be from a pedagogical standpoint. The wide range likely reflects various in teaching styles across residency programs. A related observation is that some non-trivial correlations were observed over Subject Number. This ordinal effect is almost certainly coupled to the fact that participants were ordered in groups based on their home institution as a matter of scheduling convenience.

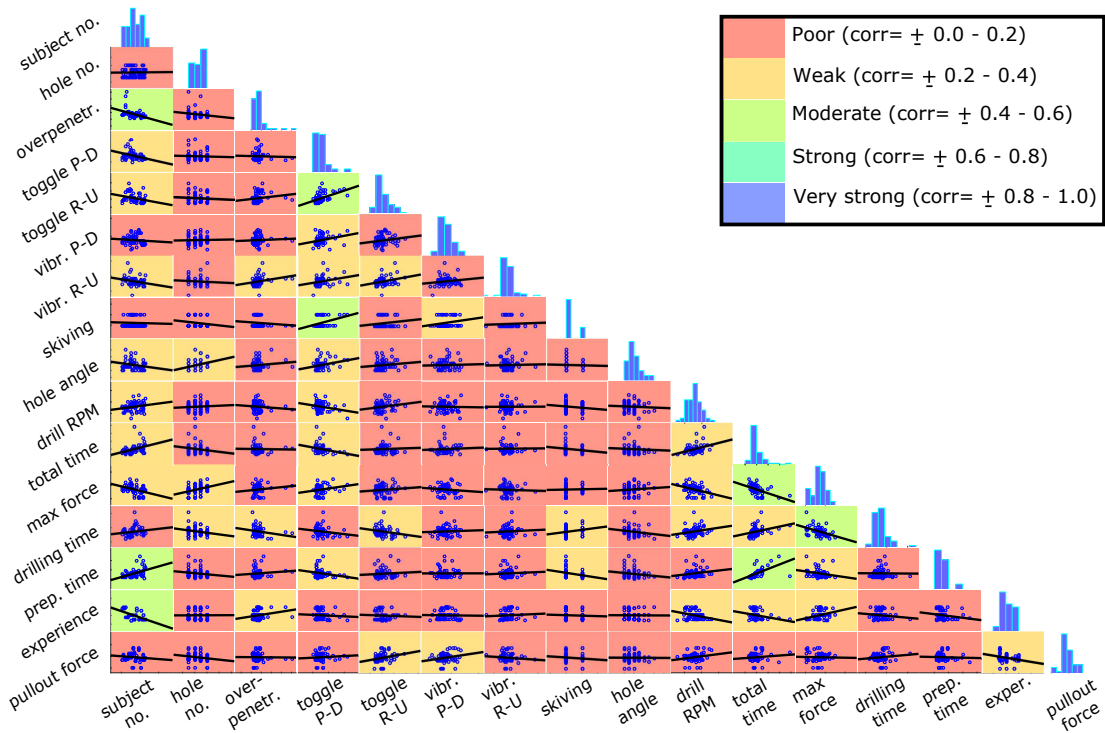


Figure 2.13: Correlation matrix for the performance parameters measured during the pre-course task. The matrix below shows the correlation between each pair of parameters. Also, scatter plots of the variables are shown after outlier rejection. The slope of the lines in each box is equal to the related correlation coefficient (slope of ± 1 equivalent to perfect positive/negative correlation). Histograms of the variables are shown along the matrix diagonal.

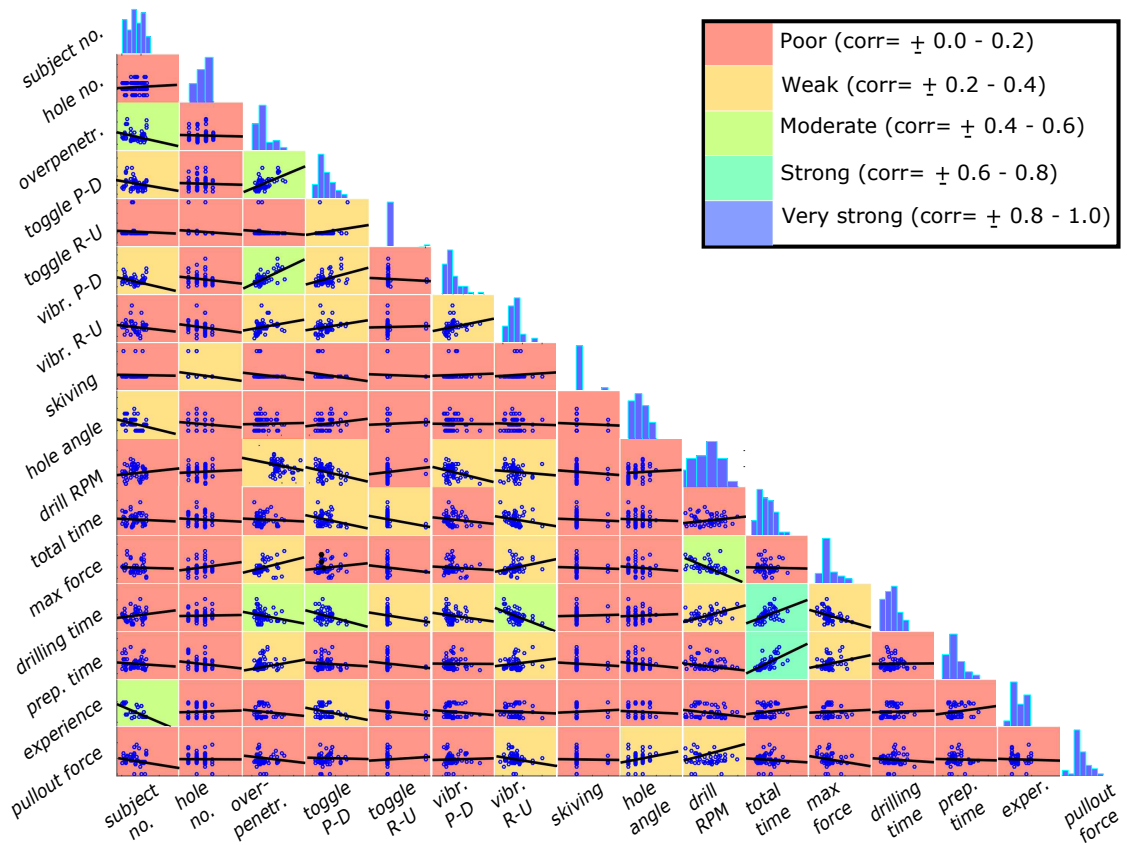


Figure 2.14: Correlation matrix for the performance parameters measured during the post-course task. The matrix below shows the correlation between each pair of parameters. Also, scatter plots of the variables are shown after outlier rejection. The slope of the lines in each box is equal to the related correlation coefficient (slope of ± 1 equivalent to perfect positive/negative correlation). Histograms of the variables are shown along the matrix diagonal.

Variable	Average Score (Pretest)	Standard Deviation (Pretest)	Average Score (Posttest)	Standard Deviation (Posttest)	Pre- Versus Post-Test (p value)
Over-penetration ^a [mm]	28.8	54.8	18.3	18.7	0.322
Toggle in P-D ^b [deg]	3.94	13.0	1.40	0.93	0.499
Toggle in R-U ^b [deg]	30.4	97.5	44.3	118	0.169
Vibration in P-D ^c [m/s ²]	1.76	0.910	2.05	0.755	0.001
Vibration in R-U ^c [m/s ²]	0.7	0.414	0.707	0.478	0.772
Skiving ^d [%]	22	42	6	24	0.009
Hole angle ^e [deg]	1.7	1.6	1.4	1.1	0.222
RPM ^f [cycles/min]	917	77.2	944	72.1	0.074
Drilling force ^g [N]	58.56	31.75	84.30	44.88	0.004
Total time ^h [s]	35.6	39.0	19.0	7.97	0.576
Preparation time ⁱ [s]	27.3	38.4	9.65	6.34	0.012
Drilling time ^j [s]	8.28	7.04	9.35	4.56	0.002
Pullout force ^k [N]	0.938	0.420	0.894	0.393	0.905

^a Maximum distance the drill bit protrudes through the distal surface.

^b Range of angles in the corresponding plane during drilling (entire hole).

^c Mean of the values reported from the corresponding axis of the accelerometer (entire hole).

^d If the subject was observed to skive while beginning to drill, it was noted by the experimenter.

^e Deviation from perpendicular, measured retrospectively using a custom goniometer fixture (X-Z plane).

^f Maximum observed during the final four seconds before the drill reaches maximum depth.

^g Maximum applied force during drilling.

^h Measured from the time the experimenter provides the instruction to begin until the time they pull out the drill bit.

ⁱ Measured from the time the experimenter provides the instruction to begin until the drill begins to rotate.

^j Total time minus preparation time.

^k Specimens were mounted to a modified angle vise that allowed positioning the screws in line with the test actuator. A ramped load was then applied using an MTS 858 Mini Bionix II frame following a protocol described in [42].

Table 2.1: Bone drilling performance averaged across 25 year-one orthopaedic residents from seven institutions.

Additionally, interesting difference by residency program can be seen in the data. Variations in pedagogical approach can be quite notable across residency programs. In Figure 2.15 key performance results are shown for each residency program. In Figures 2.16–2.21, even greater detail is provided by presenting select combinations of performance parameters for each program. An ANOVA statistical test was performed to determine which pairs of data were separated to a statistically significant degree. Taking a p-value of 0.05 as the threshold, noteworthy differences include: over-penetration (School B distinct from all other schools); toggle in the P-D (four school pairs) and R-U (two school pairs) directions; and both drilling force and drilling time for three school pair-wise comparisons.

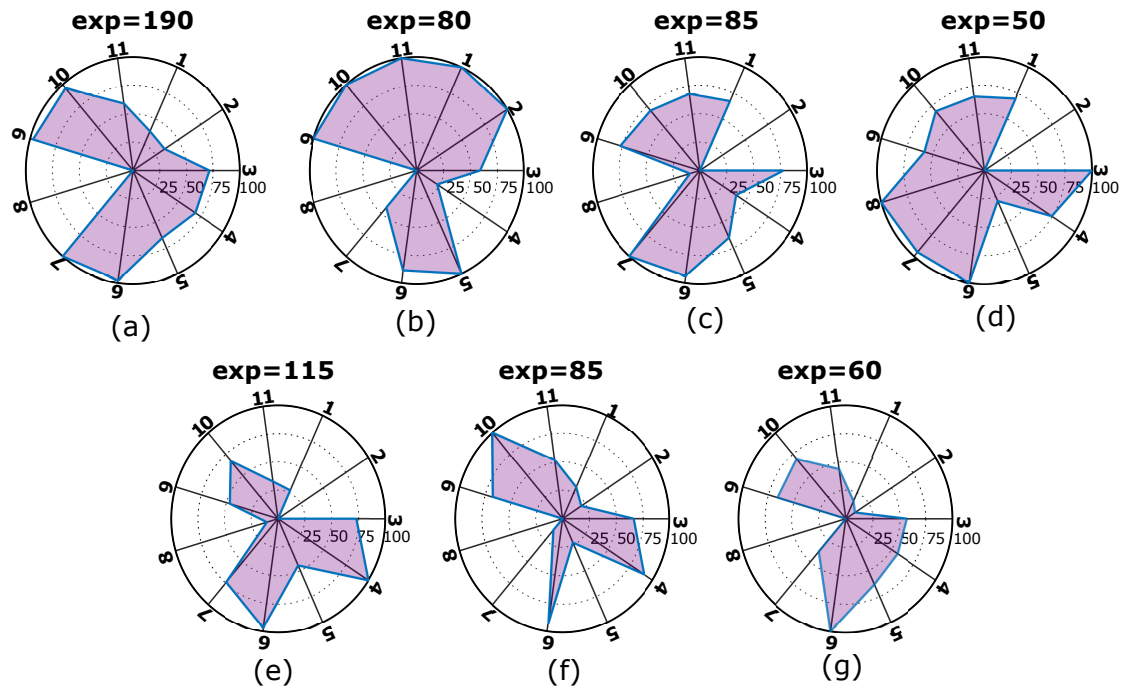


Figure 2.15: Shown are 11 selected performance parameters for each residency program (a-g), allowing a comparison of performance across program. These values shown are averaged within and normalized across residency program (100% corresponds to maximum observed, large numbers always corresponding to poor performance). For each school the Experience Level is also shown in the inset text. Select parameters include: (1) toggle in P-D, (2) over penetration, (3) pullout force, (4) drill duration, (5) drill force, (6) drill RPM, (7) hole angle, (8) skiving, (9) vibration in R-U, (10) vibration in P-D, and (11) toggle in R-U. "exp" shows the average number of surgeries performed and viewed by any of the residency program's residents.

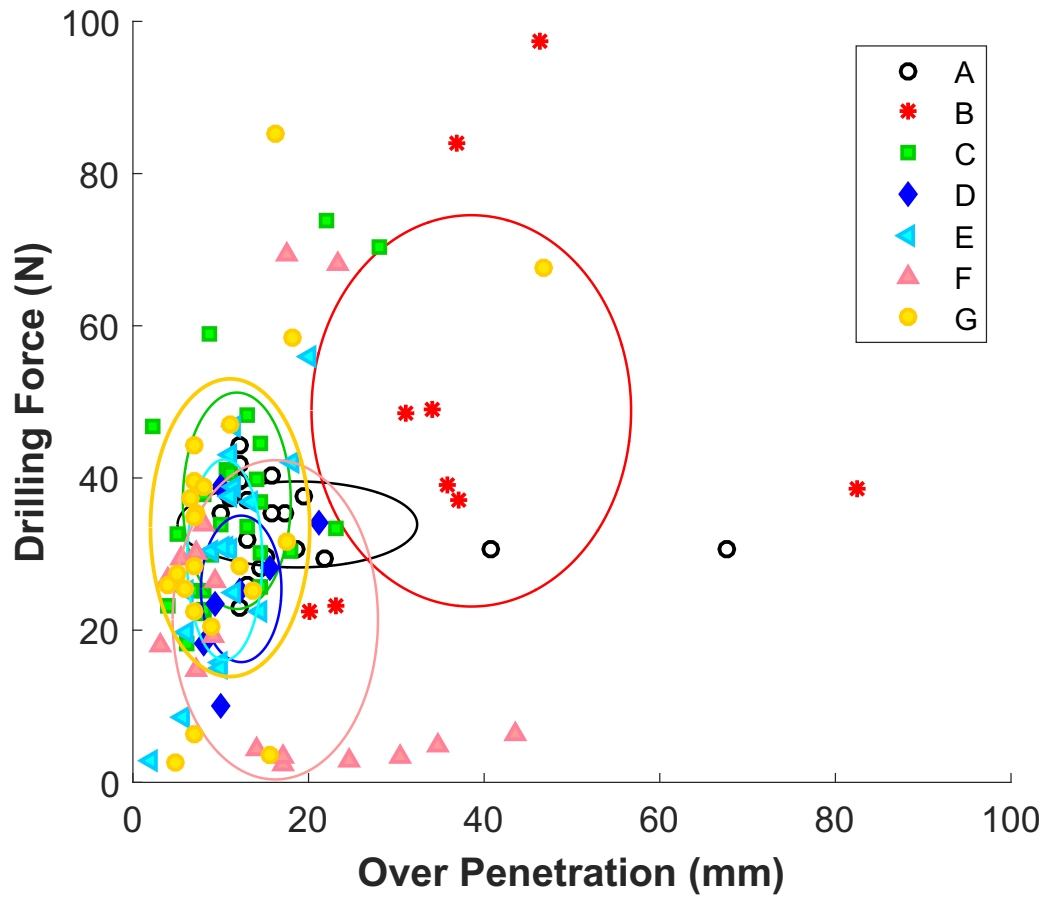


Figure 2.16: Scatter plot of drilling force versus over-penetration from performance metrics across residency programs is depicted. Ellipses are added with major- and minor-axis length given by one standard deviation in the data. A to G are the residency programs.

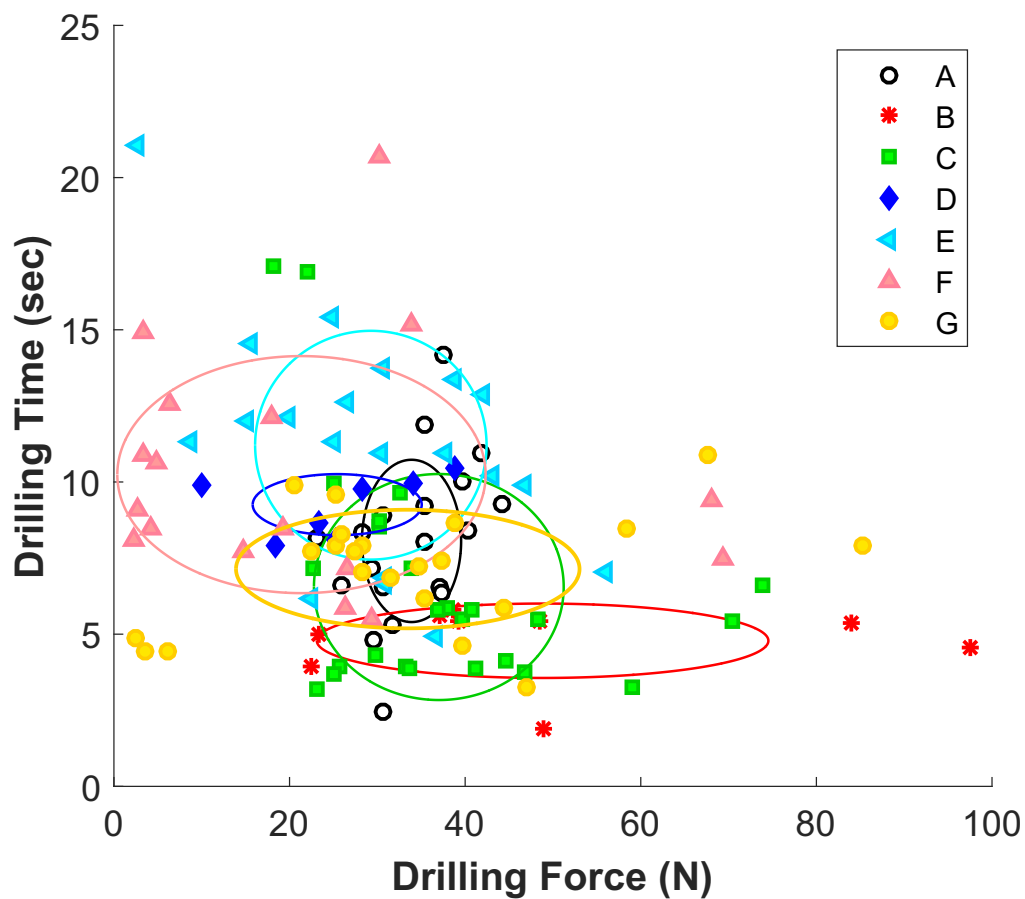


Figure 2.17: Scatter plot of drilling force versus drilling time from performance metrics across residency programs is depicted. Ellipses are added with major- and minor-axis length given by one standard deviation in the data. A to G are the residency programs.

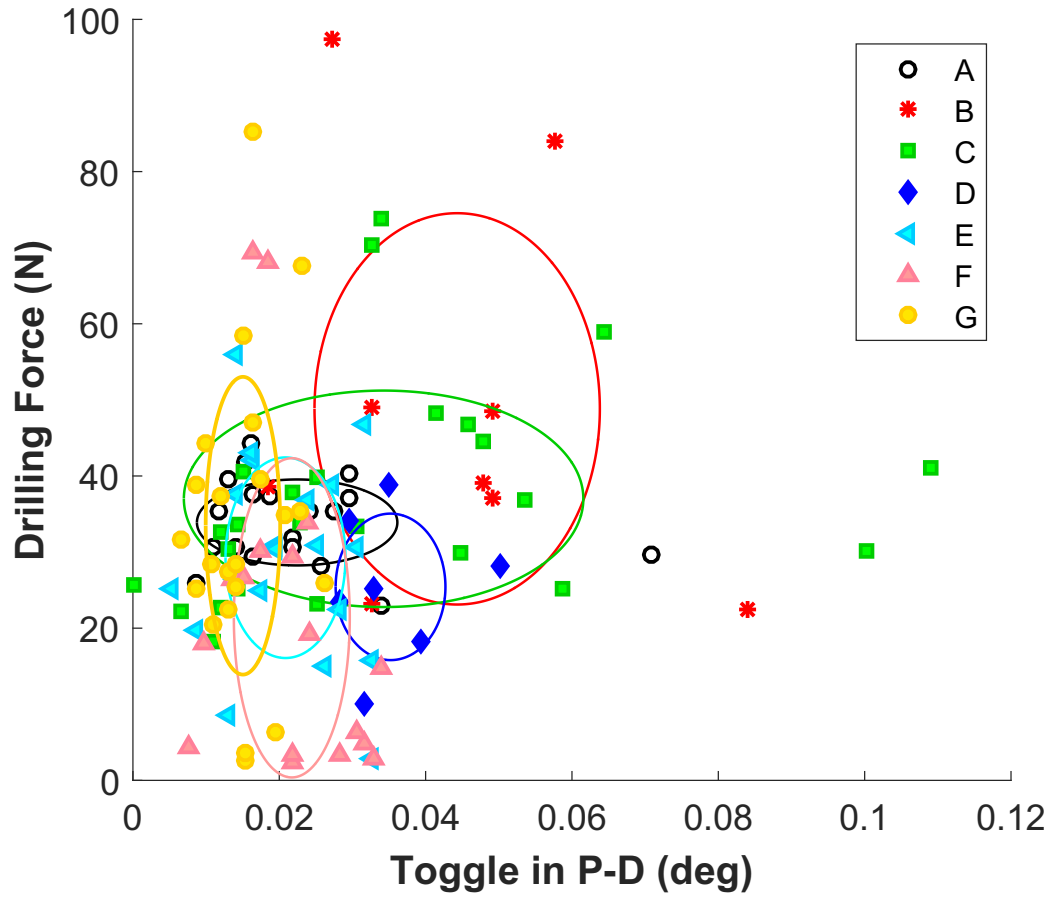


Figure 2.18: Scatter plot of drilling time versus drilling force from performance metrics across residency programs is depicted. Ellipses are added with major- and minor-axis length given by one standard deviation in the data. A to G are the residency programs.

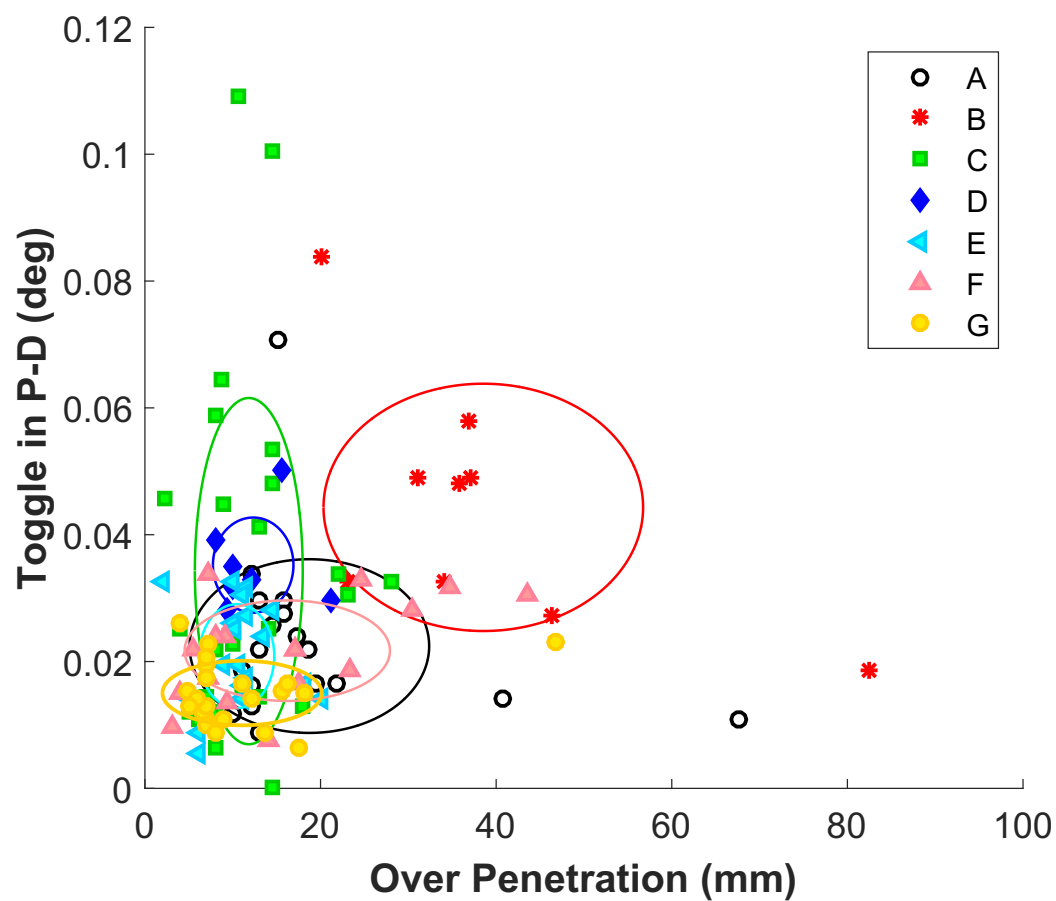


Figure 2.19: Scatter plot of toggle in P-D versus over-penetration from performance metrics across residency programs is depicted. Ellipses are added with major- and minor-axis length given by one standard deviation in the data. A to G are the residency programs.

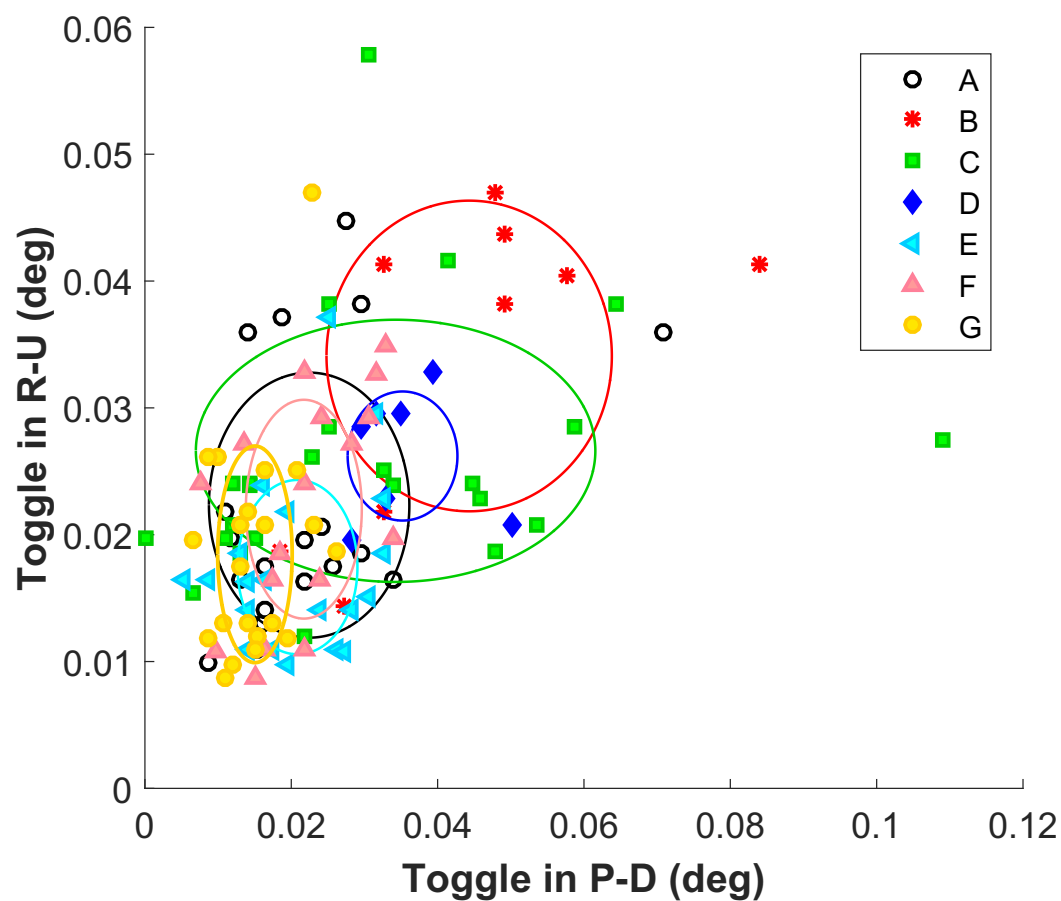


Figure 2.20: Scatter plot of toggle in U-R versus toggle in P-D from performance metrics across residency programs is depicted. Ellipses are added with major- and minor-axis length given by one standard deviation in the data. A to G are the residency programs.

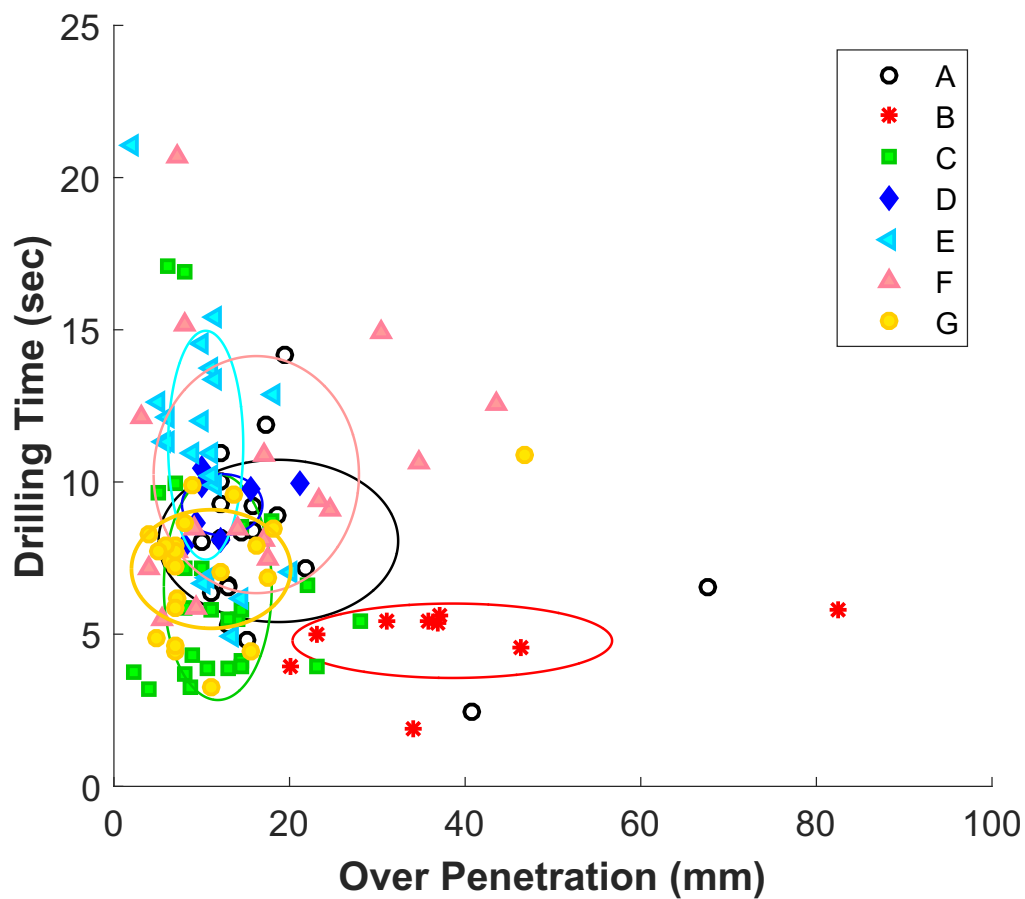


Figure 2.21: Scatter plot of drilling time versus over-penetration from performance metrics across residency programs is depicted. Ellipses are added with major- and minor-axis length given by one standard deviation in the data. A to G are the residency programs.

The survey asked residents to explain their tactics when drilling. Approximately three quarters of the responses mentioned using full RPM for at least a portion of the time and “feeling” for the distal cortex. Approximately half of the responses mentioned listening for a change in pitch associated with reaching the distal cortex. Approximately a quarter of the responses mentioned beginning normal to the proximal cortex and then acquiring the desired hold angle (as needed), changing speed as a function of depth, maintaining target angle (not toggling), and applying less pressure at the distal cortex. Three residents stated that they would “tap” the drill against the distal cortex once they determine they have reached it. One said that they generally used a slow feedrate throughout the task.

2.4 Discussion and Conclusion

In the current study, we quantified drill performance of residents before and after a motor skills course using a custom-made rotary handpiece. Performance parameters that were measured to change with statistical significance were drill vibration in the P-D direction, drill RPM, drill force, drilling time, skiving frequency, and preparation time. Given SWOTA’s intensive four-day program, which included both didactic and hands-on components, it is no surprise to see some evidence of performance improvement in the data.

High variability is evident for most of the measured parameters both within and across subjects. With much larger sample sizes additional patterns might be observed with statistical significance. A weak trend associating performance and Hole Number suggest that a more careful evaluation of this factor has the potential to show learning/adaptation on short time scales. The variability observed in the free-form responses to their drilling strategy also indicates that the residents met at SWOTA having different cues and tactics in mind. The role of tactile and auditory feedback may also merit further investigation. The noted correlations (e.g. over-penetration with drilling force P-D toggle, drilling time, and drill RPM) may help guide training protocols for orthopaedic residency programs.

Many inferences can be made regarding the correlations found. From a simple mechanics standpoint, many of these relationships can be predicted (e.g. drilling force with drill vibration and RPM). Similarly, aspects of human motor control (e.g. delay associated with proprioceptive feedback) are aligned with correlations such as that between drilling time (with associated force) and over-penetration distance as well as drill force and toggle. Hypotheses for why some changes were observed might be informed by correlations in the data. For instance, an increase in P-D vibration was observed, which may initially seem counter intuitive. However, this parameter is negatively correlated with drilling time in both pre- and post-course trials.

The correlations found should be further explored to determine where parameters are fundamentally linked by mechanics, human motor control, and as

a matter of training. In future work, we hope to explore the difference in performance that correlate to residency program. These differences may elucidate critical pedagogical factors. As possible, we also hope to decouple the roles of both practice and quality of initial instruction in the eventual skill an orthopaedic surgeon attains.

CHAPTER 3

PLATE-AND-CABLE (PAC) HAPTIC DEVICE FOR ORTHOPAEDIC TRAINING

3.1 Introduction

Orthopaedics is a hands-on, motor skills-demanding surgical specialty. These skills are acquired through a combination of skills courses and through practice in the operating room (OR) on simple fractures or low-risk cases. For more complicated operations or high-risk situations, motor skills tasks are simulated in the lab prior to performing the tasks in the OR. As of July 2013, prompted by the quality initiative set forth by the Patient Protection and Affordable Care Act, the American Board of Orthopaedic Surgeons (ABOS) and the Residency Review Committee (RRC) for Orthopaedic Surgery have mandated formal motor skills training outside of the OR [18, 43].

A large number of orthopaedic procedures involve drilling holes in bone. This seemingly simple element of the overall procedure involves subtle control and, when done incorrectly, can lead to significant complications. The drilling of a “good” hole entails precise location and orientation, and avoiding the use of excessive force, heating, over-penetration, toggle, or skiving [44, 45, 46, 40, 47, 39, 38].

Haptic devices have been developed for training applications ranging from repair of mechanical devices to surgery and aviation. The demands of each application relate to the particular choice of hardware developed. One obvious approach to training bone drilling would be to employ haptic devices configured for the task. However, this task is not well suited to existing, commercial-off-the-shelf (COTS) devices. First, the forces involved are highly anisotropic. In our own prior work, we have measured axial forces in excess of 30 pounds of force [41]. Secondly, large and rapid displacements in the off-axis direction are common. Furthermore, a haptic device put to use for this task would need to be able to faithfully render the complex geometry and mechanical variation with and across bone types and patients.

There are two broad groups of haptic devices, *admittance* and *impedance* [29]. Admittance robots tend to have large inertia, high friction, and large force capacity. In contrast, impedance type robots have small inertia, low friction, and low force capacity. These differences push haptic applications into two divided zones with their own behaviors. This fundamental separation leads the haptic

environments into either low impedance, but lacking the ability to render hard surfaces or having high impedance (and therefore able to render large forces), but not having the low impedance needed to maintaining transparency during rapid tool motions. Therefore, a system that benefits from both environments can open new areas for haptic applications [29].

As a result of the force and velocity anisotropy described, neither a high impedance (e.g. Cartesian table or Stewart platform) nor a low impedance device (e.g. Phantom or Delta series device) is well suited to the task. One morphological class of devices relevant to this work is cable-driven, parallel robots. By relying upon a system of thin cables to hold and move the end-effector instead of rigid links, these devices can achieve relatively low inertia and can scale to provide a large workspace. As a consequence of the low inertia, these devices can reach the required speed, but there is no 2- or 3-D cable-based device known to the authors that can generate sufficient force to react the axial forces observed during bone drilling. Moreover, many of the cable-based devices have cables arranged in a manner that might limit the orientation of an attached surgical drill beyond what is clinically normal.

Here we present a haptic device that, by means of using a plate-and-cable (PAC) architecture, realized a directionally-optimized, hybrid impedance. Effectively, the impedance of the PAC device is anisotropic in a manner that is aligned with the tool and reflecting the requirements of the drilling task.

3.2 Mechanical Design and Kinematic Modeling

3.2.1 Structural Design

To reach high force capacity and low inertia, we had to move the actuators aside and keep them stationary. This requirement leads us to a cable driven system. To allow for either large force or high speed actuation of each cable, a design that includes two DC motors, one with low impedance, one with high impedance, connected by a rapidly detachable link (Fig. 3.1). The current prototype includes only the low-mass, direct drive motors. Thus the PAC device essentially consists of two lightweight plates, riding on Teflon sliders, each pulled by Kevlar rope (hereafter "*cable*"). The design of the device is shown in Figures 3.2 and 3.3.

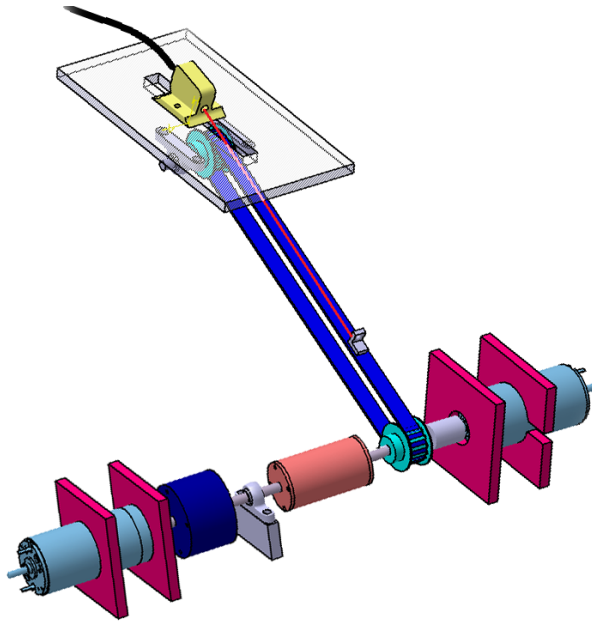
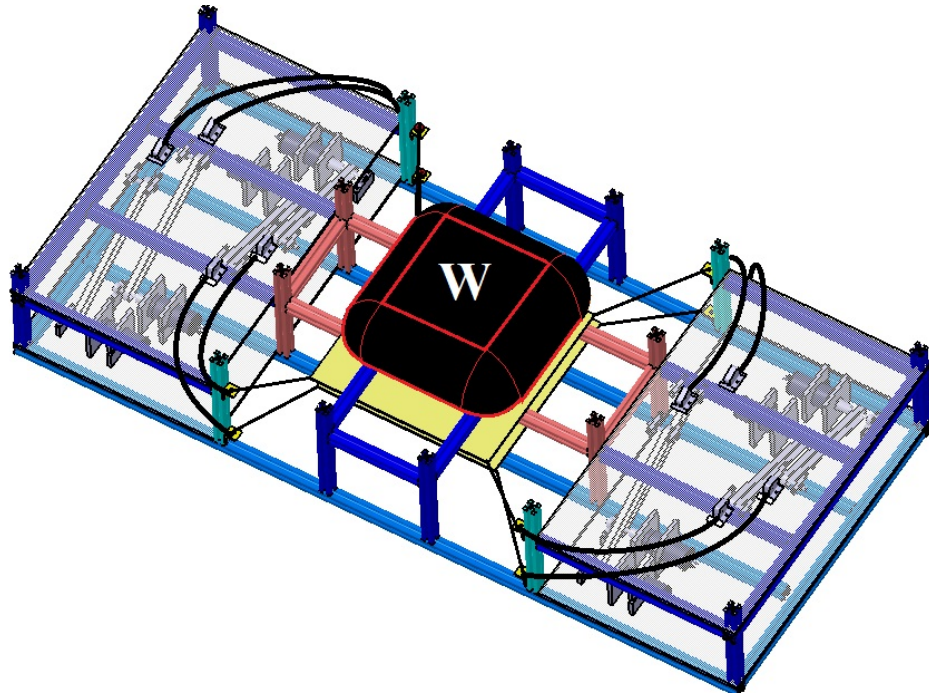
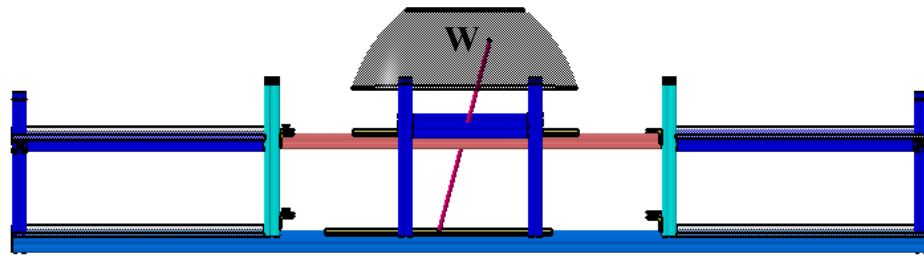


Figure 3.1: A single actuator unit is shown. Here we present our ultimate aim – two actuators are used in tandem where a high impedance actuator can be rapidly decoupled as needed to reduce overall impedance. It consists of a direct drive DC-motor (impedance mode and plate tracking), clutch, gearbox, and the second DC- motor.

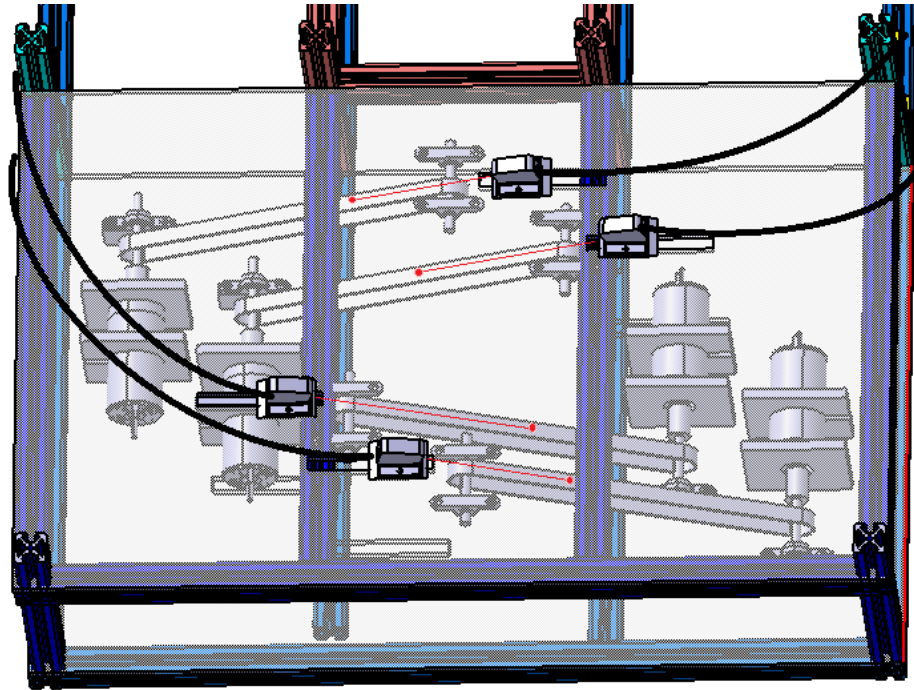


(a)

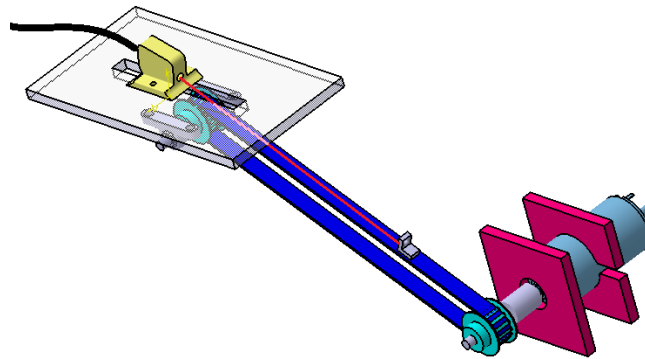


(b)

Figure 3.2: The design of the PAC is shown. At its core are two thin carbon fiber plates and their supports. A carbon fiber rod runs between them to which any number of high impedance actuators can be attached to connect orthopaedic tools (not shown) in an admittance mode, collectively providing six-DOF's. The workspace of PAC device is selected not only with bone drilling, but the use of other orthopaedic tools (e.g. pedicle awl) in mind ($6 \times 6 \text{ in}^2$ translation and 55 degree of tool pitch and yaw, except at the edges of the workspace).



(a)



(b)

Figure 3.3: To either side of the PAC device, clusters of actuator modules are mounted (a), which each pull on one corner of either plate. Each actuator module (b) consists of a brushed DC motor (Maxon 223277) and timing-belt drive train for cable control. Motor encoders are used to determine plate kinematics.

3.2.2 Forward Kinematic Model

The displacement of or tension in each cable is controlled by the corresponding actuator. Because four cables are used for each plate and given the planar constraints provided by the frame, the robot is kinematically constrained as long as all cables are taut. Key kinematic variables for the plates and tool are defined in Figures 3.4, 3.5 and Table 3.1. For brevity and to simplify the equations that follow, we define:

$$Q \equiv [L_{1-1} \dots L_{1-4} L_{2-1} \dots L_{2-4} L_t \theta_t]^T, \quad (3.1a)$$

$$R' \equiv [X_1 Y_1 \phi_1 X_2 Y_2 \phi_2 Z_1 Z_2 \theta_t L_t]^T, \text{ and} \quad (3.1b)$$

$$R \equiv [X Y Z \alpha \gamma \beta]^T. \quad (3.1c)$$

The forward-kinematic equations for the PAC Device, which relate end-effector positions and orientations to the eight cable lengths plus the length and angular position of the tool-attachment rod. This mapping from 10 inputs to 6 outputs is reflective of the unilateral constraints provided by the cables and the rotational null space between ϕ_1 , ϕ_2 , and β . We separate the forward kinematics into two separate steps ((3.1a) to (3.1b) and (3.1b) to (3.1c)). In **Step One**, we follow the method proposed in [48] to obtain plate position and orientation from (3.4). A Newton-Raphson-based solver was written for this step, which handles the one redundant DOF involved for each plate by constraining $\phi_1 = \phi_2 = 0$.

$$\text{Step One : } Q = \begin{bmatrix} L_{1-1} \\ L_{1-2} \\ L_{1-3} \\ L_{1-4} \\ L_{2-1} \\ L_{2-2} \\ L_{2-3} \\ L_{2-4} \\ \theta_t \\ L_t \end{bmatrix} \Rightarrow R' = \begin{bmatrix} X1 \\ Y1 \\ \phi_1 \\ X2 \\ Y2 \\ \phi_2 \\ Z1 \\ Z2 \\ \theta_t \\ L_t \end{bmatrix} \quad (3.2)$$

$$\text{Step Two : } R' = \begin{bmatrix} X1 \\ Y1 \\ \phi_1 \\ X2 \\ Y2 \\ \phi_2 \\ Z1 \\ Z2 \\ \theta_t \\ L_t \end{bmatrix} \Rightarrow R = \begin{bmatrix} X \\ Y \\ Z \\ \alpha \\ \gamma \\ \beta \end{bmatrix} \quad (3.3)$$

$$\begin{aligned} L_{i-j}^2 &= X_i^2 + Y_i^2 + B_{(i-j)_x}^2 + B_{(i-j)_y}^2 + A_{(i-j)_x}^2 + A_{(i-j)_y}^2 \\ &+ 2B_{(i-j)_x}((Xi - A_{(i-j)_x})\cos(\phi_i) + (Yi - A_{(i-j)_y})\sin(\phi_i)) \\ &+ 2B_{(i-j)_y}((Yi - A_{(i-j)_y})\cos(\phi_i) - (Xi - A_{(i-j)_x})\sin(\phi_i)) \\ &- 2(xA_{(i-j)_x} + yA_{(i-j)_y}) \end{aligned} \quad (3.4)$$

where: $i = 1, 2$ and $j = 1 - 4$. In **Step Two**, the plate parameters along with the length and angular position of the rod are used to determine the tool kinematics. Given this choice of kinematic variables, the azimuth (α) and altitude (γ) angles are common to the rod-plate intersections and the tool. This step has a closed form solution, presented stepwise in (3.6)–(3.10):

$$\beta = \theta_t. \quad (3.5)$$

(3.6) to (3.10) are present in this step.

$$\gamma = \cos^{-1}\left(\frac{Z_2 - Z_1}{((X_2 - X_1)^2 + (Y_2 - Y_1)^2 + (Z_2 - Z_1)^2)^{1/2}}\right) \quad (3.6)$$

$$\alpha = \tan^{-1}\left(\frac{Y_2 - Y_1}{X_2 - X_1}\right) \quad (3.7)$$

$$X = L_t \cos(\gamma) \cos(\alpha) + X_1 = \frac{L_t}{d_1}(X_2 - X_1) + X_1 \quad (3.8)$$

$$Y = L_t \cos(\gamma) \sin(\alpha) + Y_1 = \frac{L_t}{d_1}(Y_2 - Y_1) + Y_1 \quad (3.9)$$

$$Z = L_t \sin(\gamma) + Z_1 = \frac{L_t}{d_1}(Z_2 - Z_1) + Z_1 \quad (3.10)$$

Parameter	Definitions
L_{i-j}	Cable length of Plate i and Cable j
L_t	Total rod length
θ_t	Rod actuator rotation angle
X	X value of the end-effector
Y	Y value of the end-effector
Z	Z value of the end-effector
α	Azimuth angle of the rod
γ	Altitude angle of the rod
β	Roll angle of the rod
X_i	X value of the center of Plate i
Y_i	Y value of the center of Plate i
Z_i	Z value of the center of Plate i
ϕ_i	Rotation angle of the Plate i
d_1	Rod length between the two plates' centers
d_2	Rod length between the end-effector and the top plate's center
A_{i-j}	Workspace of Plate i at Cable j corner
B_{i-j}	Plate i at Cable j corner
t_j	Tension of Cable j
F_{Rx}	External force x
F_{Ry}	External force y
M_R	External torques
θ_{i-j}	Rotation angle of Cable j at Plate i
S	Static Jacobian matrix
S^+	Pseudo-inverse of static Jacobian matrix
λ	Arbitrary scalar

Table 3.1: Parameter definitions.



3.2.3 Inverse Kinematics

By exercising available controls, we can choose to set the orientation of the plates to zero, which means:

$$\phi_1 = \phi_2 = 0 \quad (3.11)$$

From there, it is useful to consider the inverse kinematics solution as consisting of two steps ((3.12) and (3.13)).

$$\text{Step One : } R = \begin{bmatrix} X \\ Y \\ Z \\ \alpha \\ \gamma \\ \beta \end{bmatrix} \Rightarrow R' = \begin{bmatrix} X1 \\ Y1 \\ \phi_1 \\ X2 \\ Y2 \\ \phi_2 \\ Z1 \\ Z2 \\ \theta_t \\ L_t \end{bmatrix} \quad (3.12)$$

$$\text{Step Two : } R' = \begin{bmatrix} X1 \\ Y1 \\ \phi_1 \\ X2 \\ Y2 \\ \phi_2 \\ Z1 \\ Z2 \\ \theta_t \\ L_t \end{bmatrix} \Rightarrow Q = \begin{bmatrix} L_{1-1} \\ L_{1-2} \\ L_{1-3} \\ L_{1-4} \\ L_{2-1} \\ L_{2-2} \\ L_{2-3} \\ L_{2-4} \\ \theta_t \\ L_t \end{bmatrix} \quad (3.13)$$

In **Step One**, we assume that we have end-effector positions and orientations. The goal is finding the center location, orientation, and height of the plates as well as the length and torsional angle of the rod. In this step, there are 6 inputs and 10 outputs. There is a closed form solution by considering the fact that Z_2 and Z_1 are constant and they are physical robot dimensions.

By using (3.10), we can get L_t :

$$L_t = \frac{Z - Z_1}{\cos(\gamma)} \quad (3.14)$$

and by substituting (3.14) in (3.8) and (3.9), we can find X_1 and Y_1 as shown below:

$$X_1 = X - (Z - Z_1) \cos(\alpha) \quad (3.15)$$

$$Y_1 = Y - (Z - Z_1) \sin(\alpha) \quad (3.16)$$

Also if we call the rod length between the top plate and the end-effector d_2 , we have:

$$d_2 = \frac{Z - Z_2}{\cos(\gamma)} \quad (3.17)$$

By substituting (3.17) in (3.8) and (3.9), we can find X_2 and Y_2 as well.

$$X_2 = X - (Z - Z_2) \cos(\alpha) \quad (3.18)$$

$$Y_2 = Y - (Z - Z_2) \sin(\alpha) \quad (3.19)$$

The last unknown is θ_t which is the inverse of equation (3.5).

$$\theta_t = \beta \quad (3.20)$$

Step Two is straightforward and just by substituting X_1 , Y_1 , ϕ_1 , X_2 , Y_2 and ϕ_2 in (3.4), we can find L_{1-1} , ..., L_{1-4} , L_{2-1} , ..., L_{2-4} . L_t and θ_t is getting passed from the last step.

If the equations are correct and if the numerical methods involved have sufficient precision, then the process of starting with some given joint variables, computing the forward kinematics, and then inverting should result in these same joint variables. This was computed for 275,000 different sets of joint variables and these two vectors (seed angles and computed angles) were compared using the l_∞ norm. Across this entire set, the greatest error was $\pm 2.6302e^{-10}$ inch, convincingly demonstrating the inverse nature of the forward and inverse kinematics equations and numerical methods involved. This does not necessarily mean, however, that the equations are correct! This is demonstrated later in this chapter.

3.2.4 Manipulator Jacobian

Using the variables defined previously, the Jacobian (J) is given by $\dot{R} = J \dot{Q}$. Just as we separated the forward kinematics into two steps, we likewise define $J = J_1 J_2$ or:

$$\dot{R} = J_1 [6 \times 10] \dot{R}' [10 \times 1] \quad \dot{R}' = J_2 [10 \times 10] \dot{Q} [10 \times 1] \quad (3.21)$$

As we see in (3.2) and (3.3), Q is the input matrix, and R is the output function. Based on this input and output, the Jacobian matrix (J) is found by (3.22):

$$\dot{R} = J \dot{Q}. \quad (3.22)$$

As we separated the forward kinematics to two steps, we found two separate Jacobians for finding final J , as shown in (3.23) to (3.26):

$$\dot{R} = J_1 \dot{R}' \quad (3.23)$$

$$\dot{R}' = J_2 \dot{Q} \quad (3.24)$$

From these two equations we could get:

$$\dot{R} = J_1 J_2 \dot{Q}. \quad (3.25)$$

Then by finding the proper J_1 and J_2 we found Jacobian as:

$$J = J_1 J_2 \quad (3.26)$$

$\dot{R}$ is a 6×1 , R' is 10×1 and $\dot{Q}$ is a 10×1 matrix then J_1 is a 6×10 Jacobian matrix, which is partial differentiation of R by R' . Also J_2 is a 10×10 Jacobian matrix, which is partial differentiation of R' by Q . Therefore we constructed the final Jacobian matrix, which is a 6×10 matrix. The Jacobians J_1 and J_2 are given by (3.27) and (3.28).

$$J_1 = \begin{bmatrix} \frac{\partial X}{\partial X1} & \frac{\partial X}{\partial Y1} & \frac{\partial X}{\partial \phi_1} & \frac{\partial X}{\partial X2} & \frac{\partial X}{\partial Y2} & \frac{\partial X}{\partial \phi_2} & \frac{\partial X}{\partial Z1} & \frac{\partial X}{\partial Z2} & \frac{\partial X}{\partial L_t} & \frac{\partial X}{\partial \theta_t} \\ \frac{\partial Y}{\partial X1} & \dots & \dots & \dots & \dots & \dots & \dots & \dots & \dots & \dots \\ \frac{\partial Z}{\partial X1} & \dots & \dots & \dots & \dots & \dots & \dots & \dots & \dots & \dots \\ \frac{\partial \alpha}{\partial X1} & \dots & \dots & \dots & \dots & \dots & \dots & \dots & \dots & \dots \\ \frac{\partial \gamma}{\partial X1} & \dots & \dots & \dots & \dots & \dots & \dots & \dots & \dots & \dots \\ \frac{\partial \beta}{\partial X1} & \dots & \dots & \dots & \dots & \dots & \dots & \dots & \dots & \dots \end{bmatrix} \quad (3.27)$$

$$J_2 = \begin{bmatrix} P_1 & & & 0 \\ & P_2 & & \\ & & 0_{2 \times 2} & \\ 0 & & & I_{2 \times 2} \end{bmatrix}, \quad (3.28)$$

where P_1 and P_2 are submatrices that we are computed numerically and describe the kinematic relationship for each plate are given by:

$$P_i = \begin{bmatrix} \frac{\partial X_i}{\partial L_{i-1}} & \cdots & \frac{\partial X_i}{\partial L_{i-4}} \\ \frac{\partial Y_i}{\partial L_{i-1}} & \cdots & \frac{\partial Y_i}{\partial L_{i-4}} \\ \frac{\partial \phi_i}{\partial L_{i-1}} & \cdots & \frac{\partial \phi_i}{\partial L_{i-4}} \end{bmatrix}, \quad (3.29)$$

In (3.28) the blocks of zeros reflect the kinematic aspects that are decoupled (e.g. plate position and orientation with respect to each other or length and angular position of rod with respect to plate parameters). The matrix below shows an example of the Jacobian for the location Plate 1 (2.5, 1.3) and Plate 2 (-2.1, -1.8):

$$10^{-2} \times \begin{bmatrix} -2 & 6 & -3 & 2 & -3 & 3 & -3 & 7 & 62 & 0 \\ 6 & -8 & 3 & -3 & 3 & -3 & 6 & -8 & 42 & 0 \\ -2 & -1 & 0 & 0 & 1 & -1 & -1 & -7 & 67 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 100 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1 & -2 & 1 & -1 & 1 & -1 & 1 & -2 & 0 & 0 \end{bmatrix} \quad (3.30)$$

Velocity of the cables is calculated based on these Jacobian matrices in the workspace. Figure 3.7 shows the velocity of one cable for one plate in three different cases. In this case the maximum velocity for each cable varies from 14 in/s to 30 in/s, which can be negative for the front cable.

3.2.5 Tension and Force Analysis

One of the most important challenges in cable driven robots is keeping the cables in tension. A static balance, accounting for cable tensions as well as external forces and torques must be determined for each plate. Following the method of [48], we solve the following for each plate:

$$F_R = \sum_{j=1}^4 \vec{t}_j = \sum_{j=1}^4 t_j \hat{L}_j \quad (3.31)$$

$$M_R = \sum_{j=1}^4 \vec{m}_j = \sum_{j=1}^4 (R \vec{b}_i) \times \vec{t}_j \quad (3.32)$$

where $\vec{t}_j$ is the cable tension for the j th cable attached to each plates. R is the rotation matrix, describing orientation of each plate. By substituting (3.31) and (3.32) the relationship between Forces and tension will be:

$$S [t_1 \ t_2 \ t_3 \ t_4]^T = [F_{Rx} \ F_{Ry} \ M_R]^T \quad (3.33)$$

The static Jacobian matrix S for each plates in our system is:

$$S = \begin{bmatrix} -\cos(\theta_1) & -\cos(\theta_2) & -\cos(\theta_3) & -\cos(\theta_4) \\ -\sin(\theta_1) & -\sin(\theta_2) & -\sin(\theta_3) & -\sin(\theta_4) \\ f_1 & f_2 & f_3 & f_4 \end{bmatrix}, \quad (3.34)$$

which for $i = 1, 2, 3, 4$ f_i is:

$$\begin{aligned} f_i = & \cos(\theta_i)(B_{ix}\sin(\phi) + B_{iy}\cos(\phi)) \\ & - \sin(\theta_i)(B_{ix}\cos(\phi) - B_{iy}\sin(\phi)) \end{aligned} \quad (3.35)$$

Because cables provide a unilateral constraint, one cable length is redundant. One solution to this problem is the positive tension method presented in [49]:

$$\vec{t} = S^+ \vec{f} + \lambda \vec{n}, \quad (3.36)$$

where 1) $S^+ = S^T(SS^T)^{-1}$ is pseudo-inverse of S , 2) $\vec{f} = [F_{Rx} \ F_{Ry} \ M_R]$ are the external forces and torques applied to the plate, 3) λ is an arbitrary scalar, chosen such that all $t_j \geq t_{min}$, which was selected to be 1 N based on measurements of the force required to eliminate cable slack, and 4) $\vec{n} = [n_1 \ n_2 \ n_3 \ n_4]^T$ is a vector that ensures this arbitrary addition does not distort the static equilibrium. This vector $\vec{n}$ is given by:

$$\begin{aligned} \vec{n} = & \begin{bmatrix} \cos(\theta_2 - \theta_3 - \theta_4) - \cos(\theta_2 - \theta_3 + \theta_4) \\ \cos(\theta_1 + \theta_3 - \theta_4) - \cos(\theta_1 - \theta_3 - \theta_4) \\ \cos(\theta_1 - \theta_2 - \theta_4) - \cos(\theta_1 + \theta_2 - \theta_4) \\ \cos(\theta_1 + \theta_2 - \theta_3) - \cos(\theta_1 - \theta_2 + \theta_3) \end{bmatrix} \\ & + \begin{bmatrix} \sin(\theta_2 - \theta_3 + \theta_4) - \sin(\theta_2 + \theta_3 - \theta_4) \\ \sin(\theta_1 + \theta_3 - \theta_4) - \sin(\theta_1 - \theta_3 + \theta_4) \\ \sin(\theta_1 - \theta_2 - \theta_4) + \sin(\theta_1 - \theta_2 + \theta_4) \\ -\sin(\theta_1 - \theta_2 - \theta_3) - \sin(\theta_1 - \theta_2 + \theta_3) \end{bmatrix} \end{aligned} \quad (3.37)$$

Figure 3.4 shows the tension of cables, force and torque of our system as well.

The maximum continuous torque of the motors is 113 mNm and stall torque is 1070 mNm. Also, size of pulley diameter is 24.05 mm. Using this information, we can calculate the maximum continuous and stall force which we can

apply to the motors as shown in equations:

$$\begin{aligned} \text{cont. force} &= \frac{\text{cont. torque}}{\text{pulley rad.}} = \frac{113 \times 10^{-3} \text{ Nm}}{12.025 \times 10^{-3} \text{ m}} \\ &= 9.4 \text{ N} = 2.1132 \text{ lb} \end{aligned} \quad (3.38)$$

$$\begin{aligned} \text{stall force} &= \frac{\text{stall torque}}{\text{pulley rad.}} = \frac{1070 \times 10^{-3} \text{ Nm}}{12.025 \times 10^{-3} \text{ m}} \\ &= 88.98 \text{ N} = 20.0035 \text{ lb} \end{aligned} \quad (3.39)$$

Figure 3.6 shows the effective tension, which has been defined in (3.40). Maximum allowable tension in our case is equal to maximum continuous force, which is 2.1132 lb based on motor specifications.

$$\text{effective tension} = 100 \times \frac{\text{max tension}}{\text{max allow. tension}} \quad (3.40)$$

Figure 3.7 shows the effective speed for 440 different locations in the workspace, which has been defined in (3.41).

$$\text{effective speed} = \frac{\text{cable speed}}{\text{plate speed}} \quad (3.41)$$

3.3 Robot Performance

Many metrics could be used to characterize device performance across the reachable workspace. The condition number of the Jacobian has often been utilized, giving insight not only into singularities and the force and velocity consequences related to proximity to a singularity [50], but also into error sensitivity (i.e. kinematic precision) [51]. Because our Jacobian encodes both position and pose information, it blends dimensional and non-dimensional units and, therefore, the condition number does not provide immediate interpretation [29]. Therefore, we present a direct evaluation of both the velocity and force implications of our Jacobian across the workspace computationally. Zargarbashi et al. proposed the following performance method. For instance if there is a small error $\delta\dot{Q}$ in the input variables of the Jacobian, it cause $\delta\dot{R}$ error in the end-effector rate. By approximation of the new Jacobian as $J(Q + \delta Q) \approx J(Q)$ we can get:

$$(\dot{R} + \delta\dot{R}) \approx J(\dot{Q} + \delta\dot{Q}), \quad (3.42)$$

which we can write it as

$$(\delta\dot{R}) \approx J(\delta\dot{Q}) \quad (3.43)$$

$$\frac{\|\delta\dot{Q}\|}{\|\dot{Q}\|} \leq \kappa(J) \frac{\|\delta\dot{R}\|}{\|\dot{R}\|}, \quad 1 \leq \kappa(J) < \infty \quad (3.44)$$

$\kappa(J)$ is condition number of J , and is bounded from below but unbounded from above; it can be written as:

$$\kappa(J) = \|J(Q)\| \|J^{-1}(Q)\| = \frac{\sigma_{max}}{\sigma_{min}} \quad (3.45)$$

which σ_{max} and σ_{min} are maximum and minimum singular values of a non-square Jacobian then the condition number of singular matrices attains unbounded values. Condition number can be used for increasing the accuracy of force application and to reduce noise propagation [50]. Next, we calculate the position errors. The results in the next section show that the robot position is very precise, meaning even if we have a large condition number, it has no effect on the position accuracy, but it can show how close to singularity our robot is. If the Jacobian condition number is low, the joint rate (in our case like cable lengths rate) of a constant magnitude, without considering the direction, is required for a given end-effector rate magnitude. Otherwise, if the condition number is higher, the magnitude of the joint rate can vary depending on its direction for a given end-effector rate magnitude [51]. In the PAC device, the condition number of the Jacobian, at all locations inspected, did not exceed 45.6368, providing confidence that PAC device kinematics are robust to encoder measurement errors.

3.4 Realization of Haptic Bone-Drilling Display

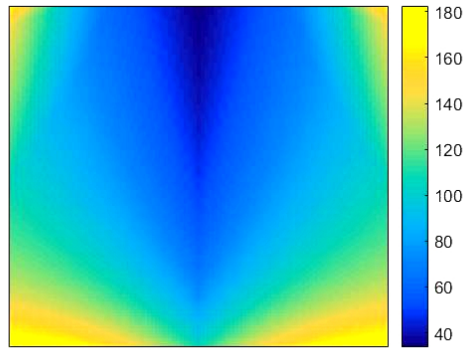
3.4.1 Structural Design

There were four main goals during the design, large force, large torque capacity, low inertia, and low friction. Therefore, we utilized two carbon fiber plates, supported with frames from top and bottom (Fig. 3.8-(a)). These aluminum frames are lined with Teflon spacers. The bottom plate provides a solid mount for the rod while allowing free angular motion except about the rod's axis (Fig. 3.8-(d)). Rotations about this axis are controlled directly by use of the cables attached to the bottom plate, typically being regulated such that $\theta_1 = 0$, thereby allowing the needed reaction torques when apply roll moments to the tool. The top plate is simply used to apply shear forces, as allowed by the integrated ball bushing (Fig. 3.8-(b,c)). Joints in both plates allow 55 degree of rotation in both the tool-pitch and yaw directions. Kevlar threads were used rather than wire rope because they provide sufficient stiffness and are much less prone to displace from the pulleys at low tension. A timing belt system proved superior to spool-based designs in early prototypes with regard to matching the motor specs and realizing a more linear system. Figure 3.3-(a) shows the design for one side of the robot, which contains four motor's modules and Figure 3.3-(b) shows these modules details. Each cable is passed through a bicycle cable housing, which has a slick-lube liner inside, to guide the cable from timing belts to the corners of middle planar module. This design also helped us to reach a higher torque capacity without having the risk of unmanaged cable. The main rod is a 12 inch carbon

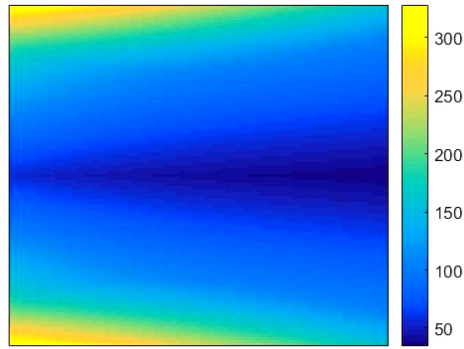
fiber rod attached to the top module that comes with a torsional and linear actuator. This overall design is essentially modular, allowing the refinement of the PAC device as well as rapidly developing related devices for other training tasks that are envisioned in future work.

Figure 3.9 shows the first prototype for this design. Wood was used instead of extruded aluminum bars, acrylic plates instead of carbon fiber, and steel rod instead of carbon fiber rod. For the motor modules, a 3D-printed housing with a pulley for the motor shaft is used instead of belt-pulley system. The circumference of the pulley was equal to the displacement.

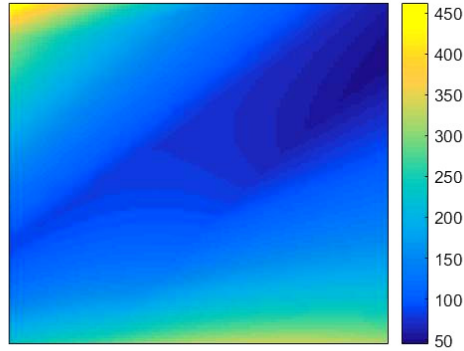
For reducing the friction between plates and the base frame, we decided to design an air-bearing system (Fig. 3.10) on top and bottom of the plates. Air bearings is a kind of bearing, which is using pressurized gas as a thin film between the surfaces for having a low friction. In this case because there is no touch between the surfaces, the mechanical problem of traditional bearing does not exist and a precise positioning without any backlash or static friction is happening. Note that implementing this module to the robot is in the area of the future work [52].



(a)

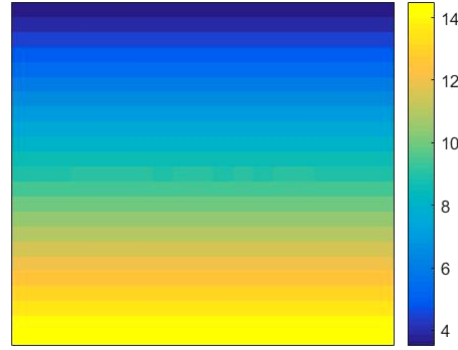


(b)

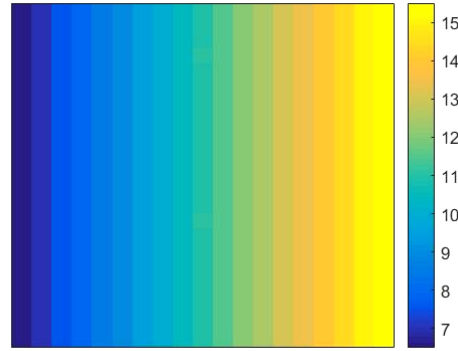


(c)

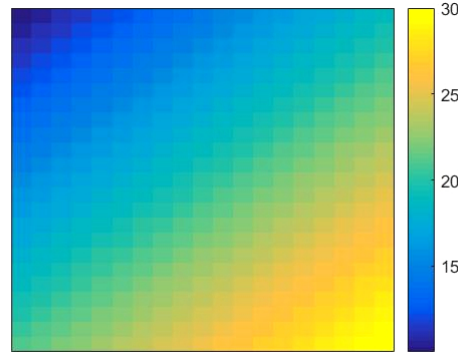
Figure 3.6: Here the relationship between motor effort and tool force is demonstrated across the PAC device workspace. Force is normalized according to (3.40), which is the effective tension and it is calculated for 275000 different sets of locations in the workspace. Values above 100 represent forces beyond that which the motors can continuously provide. In (a), the effective tension is shown while the device is simulated to provide a 1 lb external force in the x-direction. In (b), the same is shown, except that the force in y-direction. Finally, (c) shows the effective tension when we apply 1 lb external force in x- and y-directions.



(a)

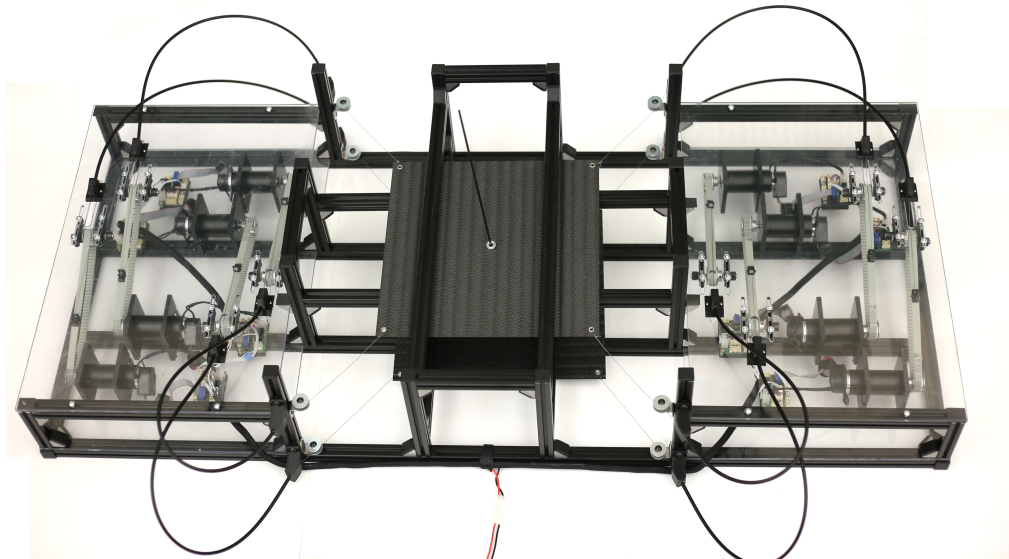


(b)

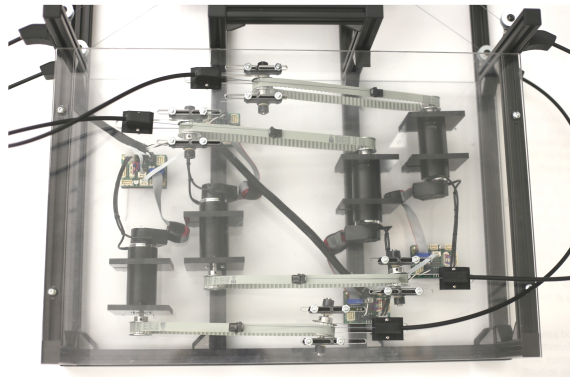


(c)

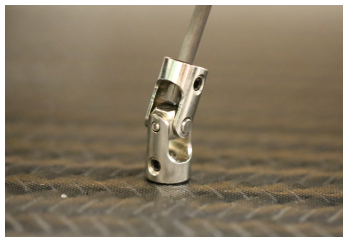
Figure 3.7: Here the relationship between actuator and tool speed is illustrated, which is calculated based on (3.41) for 440 different sets of locations in the workspace. (a) shows the velocity of plate under the constraint $\dot{x} = 1$ and $\dot{y} = \dot{\phi} = 0$. Similarly, (b) shows the velocity of plate when $\dot{y} = 1$ and $\dot{x} = \dot{\phi} = 0$. Finally, (c) shows the velocity of plate when $\dot{x} = \dot{y} = 1$ and $\dot{\phi} = 0$.



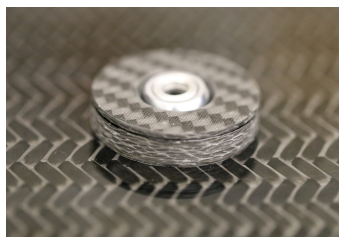
(a)



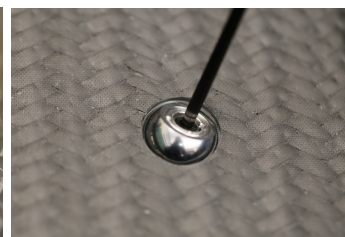
(b)



(c)



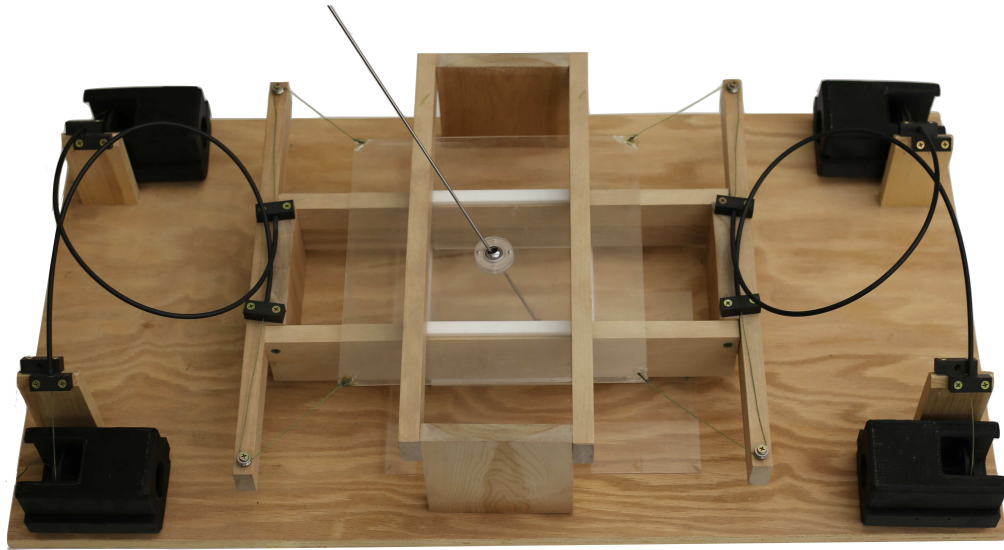
(d)



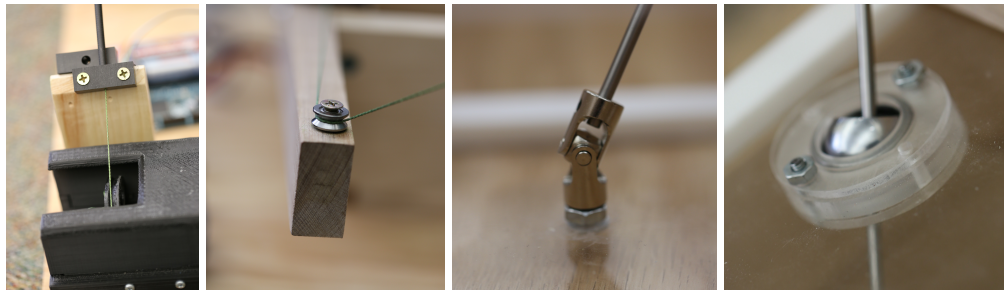
(e)

Figure 3.8

Here the design is presented in parts. In (a), the entire PAC device is shown with the exception of the computer and real-time control box. The desired orthopaedic tool is intended to be attached to the top of a carbon fiber rod. This rod is attached to the bottom plate by means of a universal joint (b). The rod then passes through a spherical bearing in the top plate (c), which is reinforced from the underside (d). The reason we have not use a ball bushing with the OD equal to spherical bearing ID was the ability to use a thinner rod, thereby allowing a larger range of tool orientation for without making the frame prohibitively large.



(a)



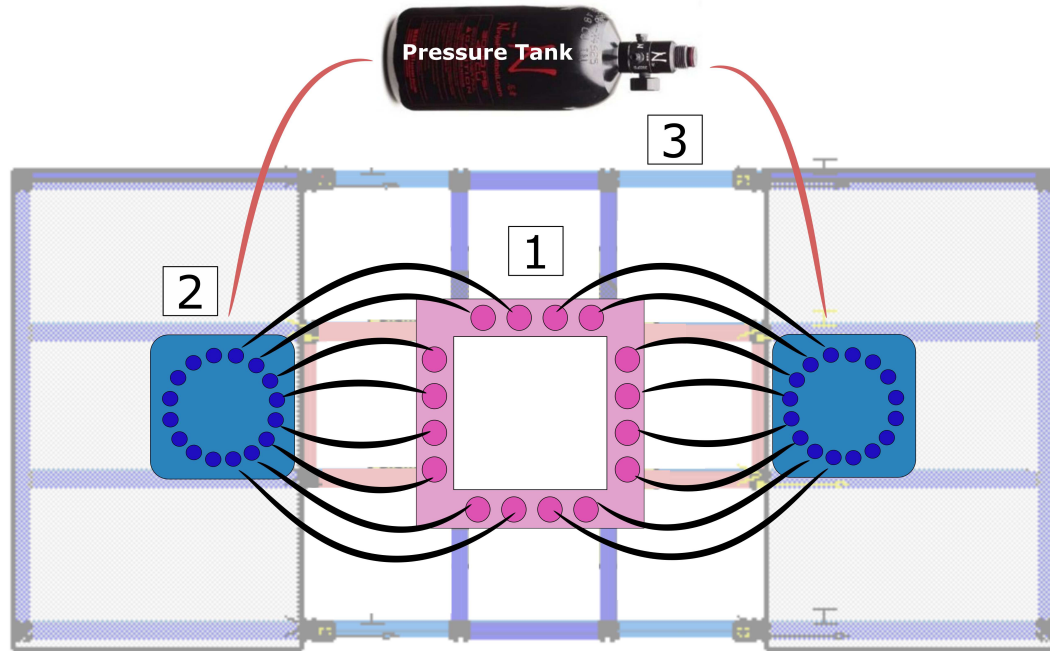
(b)

(c)

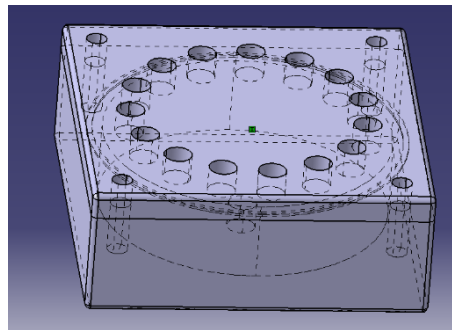
(d)

(e)

Figure 3.9: (a) shows the first prototype of PAC, which is set up for one plate connected by four cables guided to the motor housing (b) by bicycle cable, V-bearing (c) and guide. The middle rod is connected to the bottom plate by universal joint (d) and it is passed the top plate through a ball bushing press fitted in a spherical joint (e).



(a)



(b)

Figure 3.10: (a) shows the air bearing system in the PAC, which is set up for bottom of one plate. This design contains a square frame with air-nozzles under the bottom (and top) of the plates [1], which gets a very low pressure air from thin hoses connected to the nozzles in [2] by threaded to barbed-adaptor in both sides. The air supply to the [3] is from a paint ball pressurized tank, which is silent(compare to a compressor) and sufficient capacity. (b) is shown the (a)-[2] module design, which has several channels inside to conduct the air from air supply to the air nozzle.

3.4.2 Actuator Selection

The motors that have been used for pulling the cables are Maxon 223277 brushed DC motors, which are located in the left and right control modules. Brushless motors are ideal for this type of application because they are high efficiency motors, have no friction due to the brushes, and produce no sparks while in operation. The motor's data-sheet is shown in Table 3.2. The nominal voltage for this motors is 42 V in the case that we run the motor with full speed, and the maximum continuous current is 2.15 A. Based on Ohm's law the power required for eight motors is 722.4 W, which is very high power for a normal power supply and the voltage may drop, but the point is that we are never going to use all of the eight motors in full power.

The required power supply was selected with the assumption of having 113 mNm operating torque (full motor's torque capacity) and 1500 RPM operating speed (which still is higher than required). The maximum continuous current of motors are 2.15 A, then for all eight of them we require 17.2 A. Also, the under load voltage calculated 15.32 V from equation (3.46) .

$$V_{CC} > [\frac{U_N}{n_o} \cdot (n + \frac{\Delta n}{\Delta M} \cdot M) \cdot \frac{1}{0.9}] + 1[V] = 15.32 \quad (3.46)$$

In this equation V_{CC} is the required voltage, n and M are operating speed and torque respectively, U_N is nominal voltage, n_o is no load speed, and $\frac{\Delta n}{\Delta M}$ is the speed/ torque gradient. Also, $\frac{1}{0.9}$ shows the 90% of the PWM duty cycle and 1[V] shows the controller's maximum dropped voltage of 1 V at 5 A [53].

The model parameter for each motor, based on the Table 3.2 specification, is calculated in (3.47):

$$\begin{aligned} W &= 100 \text{ g} , R_{pulley} = 1.2 \text{ cm} \\ J_{load} &= W \cdot R_{pulley}^2 = 1440 \text{ gcm}^2 \\ J_{motor} &= 69.6 \text{ gcm}^2 \\ J &= J_{motor} + J_{load} = 1509.6 \text{ gcm}^2 \\ r_I &= \frac{K_m \cdot I_o}{n_o \frac{2\pi \text{ rad } 1 \text{ min}}{1 \text{ } 60 \text{ sec}}} = 6.195 \frac{\mu \text{ Nm}}{\text{rad/sec}} \\ r_o &= K_m I_o = 4.88 \text{ mNm} \end{aligned} \quad (3.47)$$

R is the terminal resistance, L is the terminal inductance, K_m is the torque constant, J is the inertia, R_{pulley} is the radius of pulley and W is the load wight. And, r_I and r_o are viscous and coulomb friction, respectively.

These motors along with the HEDL 5540 encoders, counts 500 pulses per revolution (PPR). Having high encoder PPR cause a high resolution and better

Motor Data (118778)		
1 Assigned power rating	W	90
2 Nominal voltage	Volt	42.0
3 No load speed	RPM	7530
4 Stall torque	mNm	1070
5 Speed/ torque gradient	RPM/mNm	7.17
6 No load current	mA	93
7 Starting current	A	20.3
8 Terminal resistance	Ω	2.07
9 Max. permissible speed	RPM	8200
10 Max. continuous current	A	2.15
11 Max. continuous torque	mNm	113
12 Max. power output at nominal voltage	W	206
13 Max efficiency	%	86
14 Torque constant	mNm/A	52.5
15 Speed constant	RPM/V	182
16 Mechanical time constant	ms	5
17 Rotor inertia	gcm ²	69.6
18 Terminal inductance	mH	0.62
19 Thermal resistance housing-ambient	K/W	6.2
20 Thermal resistance rotor-housing	K/W	2.0
21 Thermal time constant winding	s	29

Table 3.2: Datasheet

control dynamic. The feedback of change in the position is obtained faster and the required corrective action is sending quicker. Also, higher controller amplification causes higher stiffness, which reduces the oscillation [54].

3.4.3 Motor Controller Selection

Based on the motor specifications we chose a Maxon EPOS4 Compact 50/5 CAN (50 V, 5 A).

The EPOS4 controller is a very small size, high power density, high performance, high efficiency (up to 98 %), and suitable for both brush and brushless motors. It has the ability of effective and dynamic control of various sensors, such as hall sensors, incremental encoders, and absolute sensors (up to 750 W cont. power and 1500 W peak power) [55]. All of the specifications of these controllers are matched with the motor requirements. Based on the data-sheet of these modules, they do not have any internal motor choke. The ripple current that is flowing through the motor could get very high if there is a high supply voltage with a very small amount of terminal inductance. This can cause control instability and heat up the motor. For this reason, minimum terminal inductance, which is necessary for each phase is calculated by:

$$L_{phase} > \frac{1}{2} \cdot \left(\frac{V_{CC}}{6 \cdot f_{PWM} \cdot I_N} - (0.3 \cdot L_{Motor}) \right) = -8.9e^{-5} \quad (3.48)$$

In this equation, L_{phase} is the external inductance for each phase, V_{CC} is the operating voltage, I_N is the nominal current of the motor and, L_{Motor} is the terminal inductance of the motor. The negative result in this equation shows that there is no need for additional chokes [53].

If we want to simulate a virtual-wall by the haptic device, the hardest surface that we can render to be stable, is calculated by (3.49)

$$\min\left(\frac{2r_I}{T}, \frac{2r_o}{500}\right), \quad (3.49)$$

In this equation, 500 is the encoder PPR, T is the sampling period of the system, which we consider it 50 ms for the PID that we want to use. The parameters r_o and r_I were calculated for our model in (3.47) but we have to add the r_o and r_I of the cable and plate to these values as well. This Device has position, velocity, and torque control with various types of operating modes: (Profile Position Mode (PPM), Profile Velocity Mode (PVM), Homing Mode (HMM), Cyclic Synchronous Position Mode (CSP), and Cyclic Synchronous Torque Mode (CST)). It's different operating modes, various command options, Field Oriented Control (FOC) feature, and lots of analog-digital I/O pins, enable us to optimize and improve our robot in the future if we needed [54, 56].

EPOS controllers can work with "EPOS studio" user interface, for start-up, tuning,

parametrization, and doing constant control tasks. But, fortunately, they have libraries for different programming software like LabView, Visual C++, Visual C#, and Borland C++. We used Microsoft Visual Studio C++ for programming.

After one time set-up, the parameters could be saved permanently, even after restarting the system. EPOS4 then uses these parameters for the future commands.

3.4.4 Motor Controller Communication Architecture

The EPOS4 controllers act as slave node in CANopen network, which is a CAN bus communication protocol. These slaves get commands from a master, which controls the processes. This communication is fast because the slaves receive and execute commands without storing them. The way that data is transmitting described by a CAN bus, and the kind of data that are transmitting described by CANopen. Each bus has 127 nodes, 1 Mbit/s maximum bit rate, and 100-130 microseconds CAN telegram length at the maximum bit rate. Each of the PAC motors get an address from one of these nodes and it mounts on the bus in parallel (Fig. 3.11). To prevent signal reflection, 120 ohm termination resistors are required on both sides of the CAN bus line. A CANopen device consists of three different units. The *communication unit* contains all of the CAN communication features. The *application unit* is performing the function of the device, which in our case is a motion controller. *Object Dictionary* is the link between the application and the CANopen communication. The input data from object dictionary is getting used by the application to perform the task and then the output is writing to the same object dictionary. The parameters of the device's properties like the communication channels, all of the settings, configurations and input-output data are including in the Object Dictionary. In EPOS studio the parameters in Object Dictionary is accessible. Each parameter has a specific index to call [54].

3.5 Design of Software Development Kit

During this project, we consider the future application of the device, so we designed a user-friendly software development kit (SDK). There are two main classes in the SDK, Motor, and Plate. The class motor has properties such as Device name, protocol stack name, port name, node ID, length to degree gain, cable length, maximum current, home offset, reverse or forward (based on the orientation of motor) and functions such as CloseDevice, OpenDevice, EnableDevice, DisableDevice, GetStep, SetStep, SetCurrent, GetCableLen, SetCableLen, SetGain, len2step, step2len, SetDirection, SetHome.

The class plate also comes with properties such as position location and orientation and functions such as GetPosition, GetMotorPosition, SetPosition, SetMotorPosition, SetMotorCurrent, SetForce, SetHome, DisablePlate, FW-kin, Inv-Kin, TightPlate, GetMotor, GetMotorLength.

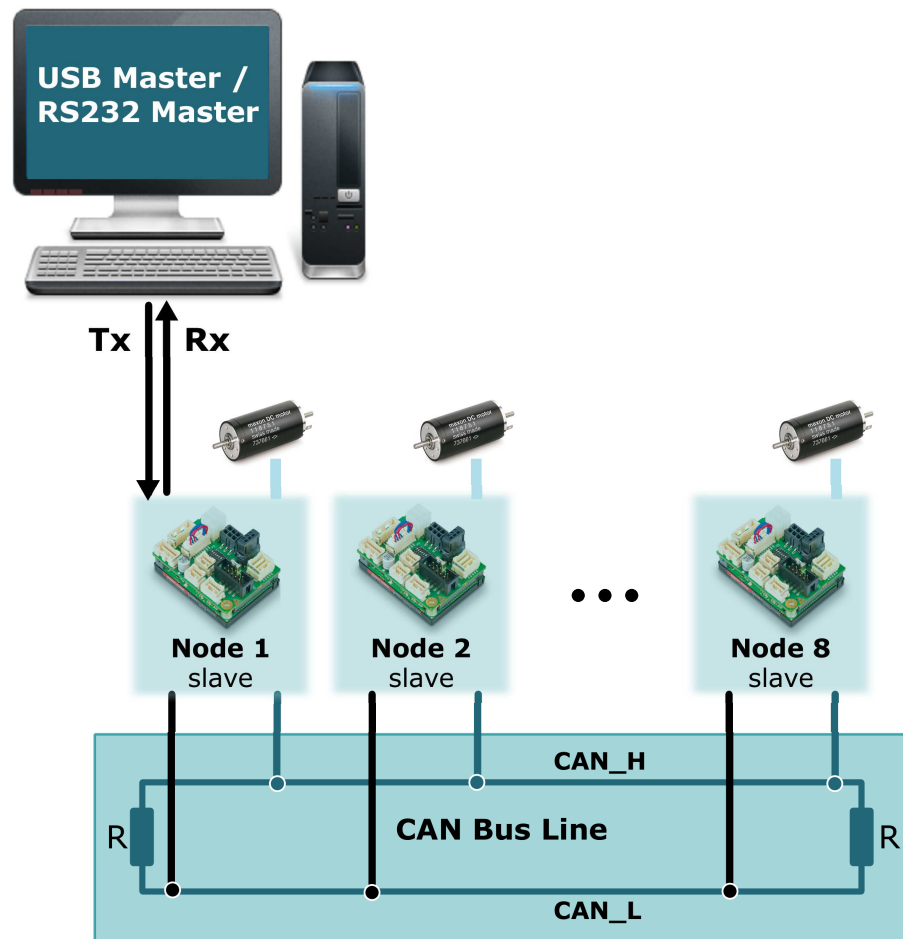


Figure 3.11: Architecture of master-slave and physical communication of CAN bus.

The SDK followed the necessary structure to communicate with "CHAI3D", which has functionalities such as collision detection, interaction, force, and torque calculator (computer haptics) in real-time simulation [57].

3.5.1 PID Controller Design

When operating the PAC device is in closed loop force control mode, the manufacturer supply routine for controller calibration works sufficiently well. An example of this tuning outcome is shown in Figure 3.12. Therefore the default control settings are used.

By contrast, when operating the PAC device is in position control, unlike force control, where nothing must known about attached load, controller should tuned given attached load.

Users of the PAC SDK can directly modify gains for either the force- or position-control modes. For the former, the gains can be set in EPOS Studio. For the latter, gains can be modified in the SDK itself. Care should be taken to note that both define error in terms of encoder steps and approximate time, but the gains are defined in EPOS Studio (for subtle reasons) to be one thousand times greater than what would be intuitive and the way they are defined in the PAC SDK.

This tuning in PAC SDK was done empirically using the manual, close loop , Ziegler-Nichols method (Fig. 3.13).

3.6 Position and Force Validation

Given that we have already demonstrated that forward and inverse kinematics equations are actually inverse of each other, it simply remains to demonstrate that one or other is correct. We chose to use the inverse kinematics equations for this ((3.12) and (3.13)). In table 3.3 a number of target positions are given along with the actual measured PAC device. Errors are calculated by (3.50).

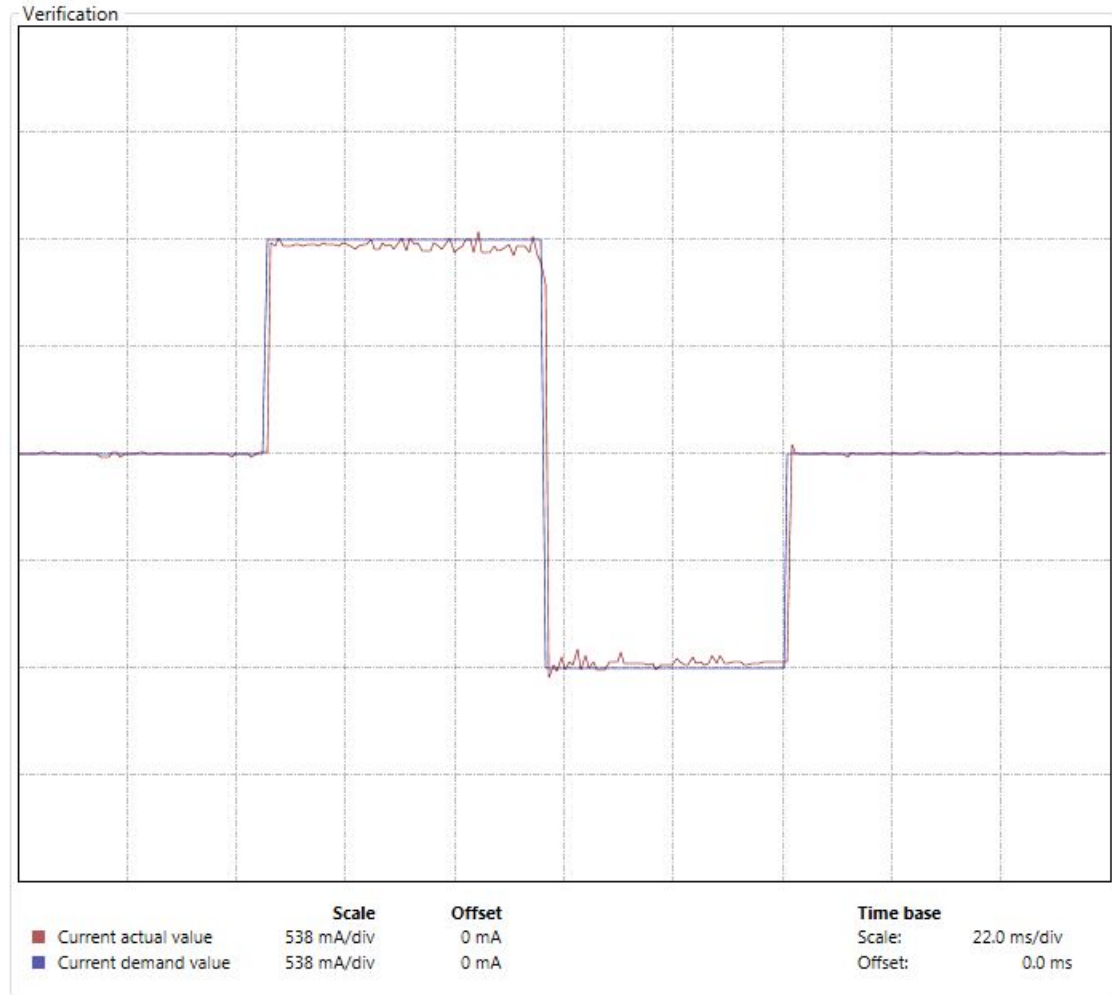


Figure 3.12: Screenshot of current control loop tuning by EPOS studio with medium stiffness, 1075 mA step amplitude, 3418.367 mV/A K_p , 14379.195 mV/(A*ms) K_i . The showing signal is square wave with 50 ms period, 1075 mA amplitude peak, and 0 mA offset.

Reference Position (mm) $[X_{ref}, Y_{ref}, \phi_{ref}]'$	Actual Position (mm) $[X_{act}, Y_{act}, \phi_{act}]'$	Location error (%)
[10 , 10 , 0]	[11 , 11 , 0]	10
[-20 , 10 , 0]	[-20 , 12 , 3]	9
[20 , 10 , 0]	[21 , 11 , 2]	6
[0 , 0 , 0]	[0 , 1 , 0]	0
[20 , 20 , 0]	[21 , 24 , 5]	15
[0 , -20 , 0]	[18 , -18 , 0]	11

Table 3.3: Position validation.

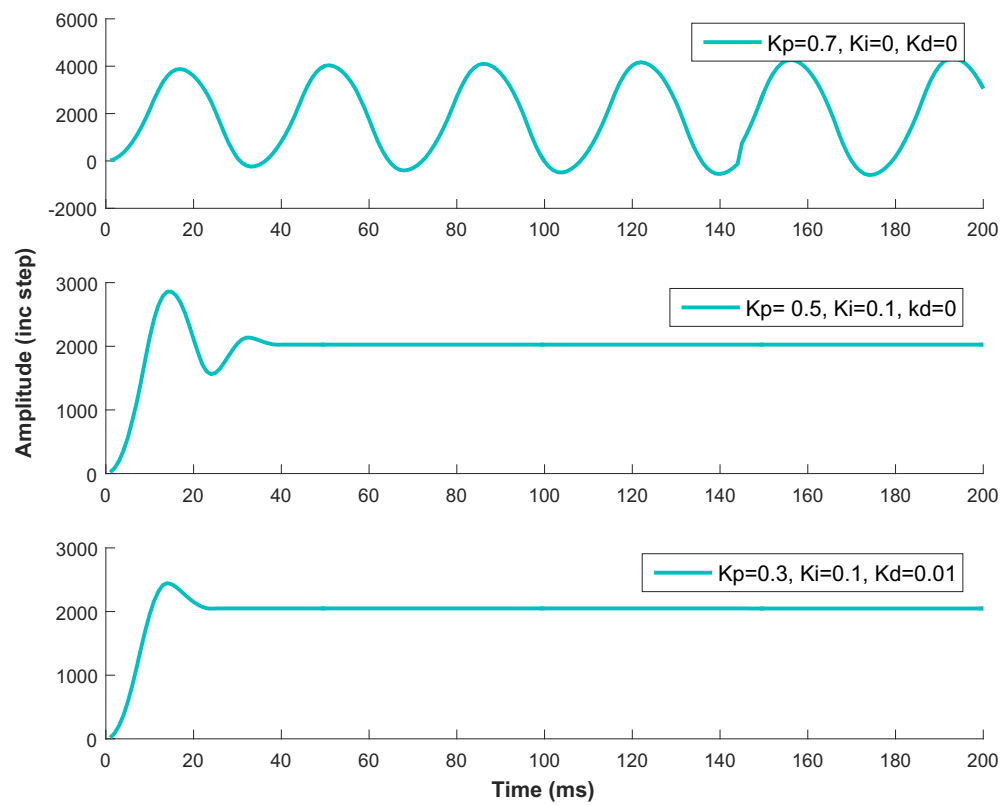


Figure 3.13: PID tuning using Ziegler-Nicholas method.

$$Location Error(\%) = \frac{\sqrt{(X_{ref} - X_{act})^2 + (Y_{ref} - Y_{act})^2}}{\sqrt{X_{ref}^2 + Y_{ref}^2}} \times 100 \quad (3.50)$$

As can be seen in Table 3.3, the position errors are 8.5 % on average. This magnitude of error is greater than we hoped but it seems to mainly arise from difficulties in hardware calibration. The primary challenge is uniformly pre-tensioning each cable given difference in friction from actuator to actuator.

In order to validate the force, (3.33) derived in subsection 3.2.5, reference plate forces, where given different reference position of PAC device (3.4). In equation (3.33) the cable tension are referenced. For these actuators, this tension is given by:

$$F_{motor} = \frac{K_T \cdot I}{r_{pulley}}, \quad (3.51)$$

where K_T is the motor torque constant 52.5 mNm and I is the motor's maximum continuous current. In practice, we have found that a minimum of 300 mA is needed to remove stiction.

For validating the force we used the equation (3.33). The validation used a digital, hand-held force sensor (Shimpo FGE-50X, Cedarhurst, NY) for measuring actual output force.

Position (mm) [X, Y, ϕ ']	Force _{ref} (N, N, N/m) [F _x , F _y , τ ']	Force _{act} (N, N, N/m) [F _x , F _y , τ ']
[10, 10, 0]	[2.0, 0, 0]	[1.7, 0.2, 0]
[-20, 10, 0]	[2.0, 0, 0]	[1.9, -0.2, 0]
[20, 10, 0]	[2.0, 0, 0]	[1.9, 0.1, 0]
[0, 0, 0]	[2.0, 0, 0]	[2.0, 0, 0]
[20, 20, 0]	[2.0, 0, 0]	[1.6, 0.2, 0]
[0, -20, 0]	[2.0, 0, 0]	[2.1, 0.1, 0]

Table 3.4: Force validation.

As seen in Table 3.4, the forces were marginally incorrect in magnitude and direction. This may be due to propagation of errors in kinematics, as some small amount of unwanted plate rotation was observed in some cases.

3.7 Conclusion

This study showed a promising result and approach to reach a hybrid device for simulating key tasks in orthopaedic surgery. The combined use of passive support of plates with actuated cables facilitates the rendering of high axial force. As shown in Figure 3.6, the continuous force, calculated in (3.38), indicates that the PAC device can bear the force in x- and y-directions, required for surgical procedure on the bone. Additional work will be done for future validation and calibration of the hardware.

CHAPTER 4

CONCLUSIONS AND RECOMMENDATIONS

4.1 Summary

This thesis explored the use of robotic tools for improving the state of the art in surgical training and simulation. This entails two projects. In chapter 2, we saw that the performance of orthopaedic residents are significantly different based on their medical residency program and training method. This difference shows that having a high precision and reliable training in the medical residency programs is very crucial. In chapter 3 we design a platform for simulating bone drilling and other procedures that require large force in one, tool-oriented direction, and low force with high speed in the orthogonal directions.

4.1.1 Orthopaedic Skill Assessment

A correlation has been found between different parameters that might affect bone drilling. Also, the difference between some of the parameters in pre-versus post-test results during the SWOTA motor skills course was significant. Additionally, interesting difference exist by residency program. The correlations found will be further explored to determine where parameters are fundamentally linked by mechanics, human motor control, and as a matter of training. Lessons learned may significantly inform new training paradigms for effective training programs outside of the operating room.

4.1.2 Cable-Driven Haptic Robot

The design, Jacobian, and evaluation of novel haptic device for uses including simulation of bone drilling has performed. The forward kinematic equations for the PAC device are derived to ensure that the plates' orientation remains constant. The corresponding equations are solved using the Newton-Raphson method. Finally, the predicted distribution of location error, cables velocity, cable tension and force for the device have been presented. These results and preliminary hardware fabrication indicate that this design may provide a revolutionary

approach for haptic display of many surgical procedures by means of an architecture that allows arbitrary workspace scaling. Scaling of the height and width can be scaled arbitrarily.

4.2 Future Work

4.2.1 Orthopaedic Skill Assessment

In future work, we hope to further explore differences in performance that correlate to residency program. These differences may elucidate critical pedagogical factors. As possible, we also hope to decouple the roles of practice and quality of instruction in the eventual skill acquisition of orthopaedic surgeons. Correlations associated with preparation time also deserve further investigation. The performance trends associated with hole number suggest the potential advantage in having a surgeon anticipate short-time-scale learning, especially when any variation in drill, drill bit, or bone is present. In the surveys that the residents completed during this study, some of them mentioned that they track the location of drill bit, while in the bone by tactile and auditory cues. The role of tactile and auditory feedback merits further investigation.

4.2.2 Cable Driven Haptic Robot

In future work, our ultimate aim is to realizing a dual admittance / impedance mode. This could be done by adding another actuator with a gearbox and a clutch to our current motor module to rapidly decoupled as needed (Fig. 3.1).

For improving the realizing of impedance mode, we have to add an air-bearing design to the top and bottom of plates for reducing friction. Also, after running the plates, we noticed that the friction in the bicycle cables still is noticeable and the cables, which had more curvature, and therefore higher friction. The housings might replaced with something like V-bearing for smoother movement.

An extra arm should added for fixing the middle rod in a home position (vertical and center) for homing the encoders accurately when it starts.

A z-axis movement tool should be connected to the top of the rod to simulate full movement in x-, y-, and z-directions. Then, hopefully, we aimed simulate haptic feedback based on the structure of different bone layers combined with a virtual environment using the Microsoft Hololens, which is a mixed reality headset.

We hope to build on lessons learned during the 2016 and 2017 SWOTA conferences, wherein surgical skill during bone drilling was carefully evaluated. For future SWOTA conferences we plan to involve the PAC device in a human subject experiment to evaluate its perceived fidelity and utility.

Acknowledgment

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My deepest gratitude goes to my parents and my brothers, Amid and Emad for supporting me spiritually throughout my life and being beside me every day in the last two years even with the far distance between us.

APPENDIX A

SURVEY

Surgical Bone Drilling Experiment Pre-Survey

1. Please enter you subject number:

2. Year of Training:
 - ☐ Medical Student or Non-Resident
 - ☐ Resident 1yr.
 - ☐ Resident 2yr.
 - ☐ Resident 3yr.
 - ☐ Resident 4yr.
 - ☐ Resident 5yr.
 - ☐ Expert
 - ☐ Other

3. What institution were you trained at for residency?

4. Estimate Number of surgery's performed and viewed:

5. When you drill, how would you describe the way you identify the location of the drill bit through the bone (i.e. full speed, half speed, straight first then angle, angle first then straight for a second, sound, time....):

APPENDIX B

PERMISSIONS

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A) Permission of Figure 1.1

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Surgery circa 1922.



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ROBOTIC TOOLS FOR TRAINING AND ASSESSMENT OF ORTHOPAEDIC SURGICAL SKILLS

by Naghmeh Zamani

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